ARPA ORDER NO.: 189-1
3P10 Distributed Information Systems

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# Computer-Based Automation of Discrete Product Manufacture: A Preliminary Discussion of Feasibility and Impact

Alexander F. Brewer, Compiler; Contributions by T. O. Ellis, G. F. Groner, D. E. Roseen and W. L. Sibley

A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

Rand
SANTA MONICA, CA. 90406

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# PREFACE

The study described in this report was initiated on October 1, 1971, at the request of the Information Processing Techniques Office of the Defense Advanced Research Projects Agency (ARPA). The original focus of the project was on the investigation of potential technological feasibility and the impact of advanced automation and robotics on DOD procurement. This report presents some preliminary findings of the investigation, including several innovative concepts for automated manufacturing processes and a rough technoeconomic evaluation of those concepts. Our evaluation is largely based on estimates; therefore, the comparisons we have made must be considered tentative. Nevertheless, the potential impact of the technological innovations considered here on both the DOD and the civilian economy is sufficiently great that publication of these preliminary results appears warranted.

The automation techniques discussed should be of interest to a wide audience, including military defense and mobilization personnel who are concerned with cost savings of manufactured items and with the need for rapid response to contingency requirements; persons concerned with computer-based automation of production and inspection devices; and computer scientists concerned with practical applications of computer technology.

It is hoped that this discussion will stimulate further investigation into those areas where we have indicated that research is urgently needed to enable informed decisions to be made about implementation of these concepts.

The direction of future Rand work, if any, in this area is uncertain. As a result of Congressional funding limitations imposed on The Rand Corporation in 1972, ARPA funding for this investigation was discontinued. This report, therefore, has been completed and published at Rand expense.

We would like to express our appreciation for helpful discussions during the course of this study with Rand staff members R. H. Anderson, M. R. Davis, G.A.R. Graham, F. J. Morgan, and R. M. Salter, Jr., and with R. M. Perry and K. W. Uncapher, formerly of Rand.

# SUMMARY

A preliminary examination of manufacturing processes currently in use in the United States indicates that the application of advanced computer science and programmable machine techniques to the manufacture of discrete engineered products could substantially increase productivity and reduce costs. The use of this type of production automation, which we shall call *programmable automation,* is considered here for all manufacturing operations, including assembly and testing, dealing with moderately to highly complex products in lots ranging from a single prototype to daily production rates approaching those for which hard automation[1] is more economic. We have used the word "discrete" to differentiate manufactured hard goods from those of the process industries, such as steel or petroleum production, which usually deal with basic materials and are generally well automated already. Discrete manufactured products for which programmable automation techniques might be appropriate would include small missiles, x-y plotters, autopilots, and movie projectors.

Programmable automation for such operations as parts forming and machining, assembly, inspection, transfer and storage of materials, tooling, inventory control, and scheduling could have the following attributes:

1. Computer control, requiring little human intervention (and therefore independent of human reaction speeds or human variability).
2. Flexibility, i.e., the same production functions could be used for manufacturing diverse products within a broad product class (for example, small electromechanical systems), design changes could be accommodated, and the process could accommodate changes in materials and manufacturing techniques.
3. Integration with computer-aided design and engineering facilities, accounting systems, and management information and control systems, enabling rapid acquisition and assimilation of information from each of these areas with a considerable reduction in communication effort.

On the basis of our examination, we have drawn the following tentative conclusions:

1. Theoretically, programmable automation appears to be technologically feasible. But we believe that its implementation will require innovations and focused development over a period of at least five years.
2. The development of programmable automation by industry is proceeding very slowly and in piecemeal fashion, for several very sound reasons. It appears that government funding and leadership would be required to realize the full potential of programmable automation.
3. The impact of programmable automation could be profound. Approximately 80 percent of the U.S. manufacturing facilities appear amenable to this type of automation. The impact is likely to occur in the following areas:
   - Increased productivity, measured either as reduced unit cost or reduced production time, or both.
   - Increased product quality and safety.

[1] The use of specialized machines to perform repetitive manufacturing tasks with great speed and uniformity. Hard-automation devices are tailored to a particular product design and are generally appropriate only for very large-volume, continuous-run production.

- A potential for decentralized production.
- Changes in management and work-force structure.
- Product innovation.

4. The cost-effectiveness of programmable automation is largely unknown and requires further detailed examination, especially after experimental data on key factory components become available.
5. The full impact of programmable automation cannot be properly assessed without an in-depth study of the economics of discrete-product manufacturing and procurement. Such a study must also take into account alternatives to programmable automation as well as the estimated research and development costs associated with each option.
6. Although the maximum impact of programmable automation will be realized only with a totally automated factory, many of the factory components are valid research and development problems and should be pursued in themselves.

We emphasize that the results presented in this report are *interim* findings, which must be subjected to thorough analysis and experimental verification before they can be considered definitive. They are being published at this time in the hope of stimulating discussion of and further research on the potential effects of advanced automation on many aspects of U.S. defense-materials procurement and the U.S. economy.

## CONTENTS

# I. BACKGROUND AND MOTIVATION FOR THIS STUDY

The productivity and responsiveness of U.S. industry are of vital importance to the Department of Defense. As weapon systems and other defense-procurement items become increasingly sophisticated and exponentially expensive, there is an urgent need to reduce the cost of manufacture, to reduce the long time required for start-up and changes, and to increase the reliability of the resulting product. Former Deputy Secretary of Defense David Packard has stated:

> The continued advancement of manufacturing technology ... must be an integral part of our effort to retain an effective mobilization base that will be responsive to any military contingency. Numerous precedents exist where innovative research and development projects have transitioned into current manufacturing application.... This has resulted in substantial product cost savings, improvements in weapon systems performance, quality, reliability, and also significant reductions in leadtime.... We must find ways to increase the amount of productivity per labor hour. I am convinced that a little "seed money" and effort spent today in the development of more advanced manufacturing methods and processes will do this and will pay for itself many times over in the future. [1]

This report discusses the potential uses of advanced computer-based technology in the manufacture of discrete products[2] and suggests innovative ideas for manufacturing machines and processes that could result in increased manufacturing productivity. This study is focused specifically on products that are electromechanical in nature, e.g., missiles, autopilots, or instruments. The techniques considered are, however, applicable to a much broader class of discrete products.

Any increase in productivity in product manufacture could result in significant cost savings to the DOD. In FY 1971, the total DOD procurement expenditure was $18.858 billion [2]. This included an estimated $10.7 billion for discrete-manufactured-item procurement.[3] As an example of discrete-product procurement expenditure, Table 1 and Fig. 1 show estimated DOD expenditures in the period FY 1972 – FY 1976 for missiles that are between 4 ft and 12 ft in length and between 5 in. and 15 in. in diameter. An average annual expenditure of $255 million is shown for these products alone, about 90 percent of which could potentially be produced using advanced automation techniques, with savings estimated at one-half or more of current costs.

In addition to the potential cost savings to the DOD there are other important reasons for investigating advanced automation of U.S. production. Recent studies show U.S. productivity gains to be one-fourth those of Japan and one-half those of many countries of Western Europe [4]. Furthermore, advanced automation could be important from the quality-of-life standpoint. The demeaning, dull nature of manufacturing tasks has been documented [5], with increasing reports of worker dissatisfaction and hostility [6]. Automated processes could relieve workers of such frustration, as a contribution to the postindustrial revolution.

[2] Discrete products are considered in this report to be hard manufactured goods. The discussion does not apply to process industries, such as steel or petroleum production, which are already well automated.

[3] Communication with Dr. N. Kamrani of the University of Southern California.

Table 1

DEFENSE PROCUREMENT EXAMPLE: ESTIMATED EXPENDITURES FOR MISSILES 4 TO 12 FT IN LENGTH AND 5 TO 15 IN. IN DIAMETER
($ millions)

| Missile | FY 1972 | FY 1973 | FY 1974 | FY 1975 | FY 1976 | Total |
|---|---|---|---|---|---|---|
| Bulldog | 15 | 5 | 1 | — | — | 21 |
| Chaparral | — | 5 | 10 | 10 | 3 | 28 |
| Dragon | — | 30 | 30 | 30 | 12 | 102 |
| Maverick | 74 | 70 | 66 | — | — | 210 |
| Posms | — | 23 | 24.5 | 11 | 4.5 | 63 |
| Shillelagh | — | — | — | 25 | 37 | 62 |
| Shrike | — | 20 | 20 | 20 | 10 | 70 |
| Sidewinder | — | 55 | 50 | 50 | 30 | 185 |
| Aparrow | — | 90 | 100 | 110 | 90 | 390 |
| Tow | — | 35 | 35 | 10 | — | 80 |
| Walleye | — | 10 | 10 | 10 | 1.7 | 31.7 |
| Zuni | — | 11 | 10.5 | 8 | 2.5 | 32 |
| Total | 89 | 354 | 357 | 284 | 190.7 | 1274.7 |

SOURCE: *DMS Market Intelligence Reports* [3].

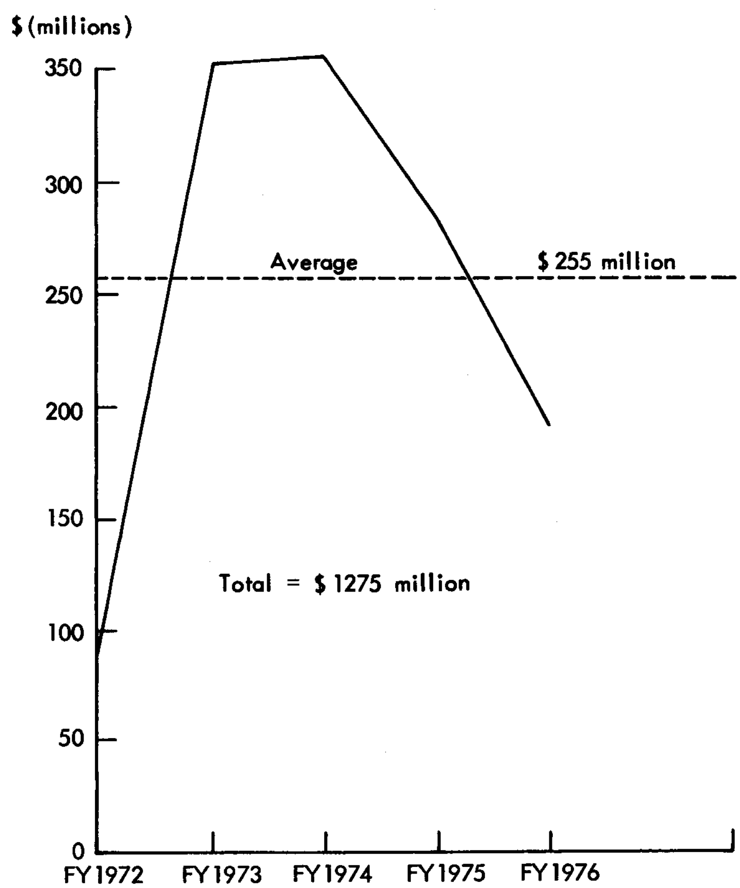



Fig. 1—Estimated DOD expenditures for missiles 4 to 12 ft in length and 5 to 15 in. in diameter

The traditional approach to increasing both productivity and product quality in large-volume production has been the use of special machines for automating some aspects of the manufacturing process. Specialized machines—so-called hard-automation or transfer machines—can perform repetitive manufacturing tasks with greater speed and uniformity than humans but are tailored to one-product design only. Because of the high cost and inflexibility of hard automation (most of it must be scrapped when a product changes), it is usually justified only for very large-volume, continuous-run production. Therefore, the benefits of automation are generally not available in industries whose products are characterized by variations in production-lot size or frequent changes in either the product or the manufacturing process. Whereas hard automation is used extensively in the automobile industry and in the production of certain military and consumer products, 80 percent of U.S. manufacturing industries, i.e., the so-called job shops, have production rates much lower than those that make hard automation economical [7].

Experience has shown that the introduction of computer-controlled machines in the manufacturing process can produce dramatic payoffs. Numerical control (N/C) of machine tools,[4] first by magnetic or punched paper tape and more recently by centralized digital-computer control or local minicomputer control, allows machining operations to be performed at one-fifth the time and cost required by manual methods [8]. Figure 2 shows the dramatic decline in the cost and time of machining operations as the degree of automation is increased. The "variable mission system," showing a decrease by a factor of 4 to 10 in manufacturing cost per piece (as compared with manually operated machines) in the job-lot and prototype regions, comprises a group of N/C part-cutting machines with computer-controlled piece transfer between machines and with automatic machine loading and unloading.

The automation concept we examine in this report extends the philosophy of direct programmable computer control to nearly all aspects of product manufacture (parts shaping, assembly, test, transport, storage, scheduling, routing, etc.).[5] Our preliminary studies indicate potential cost and time savings for the entire discrete-product manufacturing process comparable to those that have revolutionized machining operations.

With the increasing sophistication of computer-science techniques, especially in the fields of artificial intelligence, pattern information processing, robotics, and management information and control systems, the potential exists for a much broader application of computer technology to discrete-product manufacturing. Flexible, programmable, computer-controlled automation—which we shall call *programmable automation*—is already being introduced into many discrete-product manufacturing processes (for many product classes), including aspects that traditionally have not been amenable to automation: assembly, logistics, inspection, and quality control. However, even more important than the automation of these individual elements is the potential of programmable automation for the integration of the

[4] An N/C milling machine, for example, is capable of moving the workpiece relative to the cutter in three orthogonal coordinates. Each axis is controlled by a digital servomechanism and receives digital commands from a magnetic tape. The three axes may be commanded to move simultaneously and at different speeds to produce a three-dimensional contour in the workpiece. Various on-off functions such as the spindle motor, clamps, and coolant pump are also digitally commanded. Some N/C milling machines use magnetic or paper tape to command end points of a particular cut only, and an "interpolator" at the machine tool provides the required digital inputs to the servomechanisms.

Another example of an N/C machine is a turret punch, equipped with a variety of hole punches and a table capable of x-y motion. A punched paper tape is usually used to command table motion and punch selection. Such a machine is used for perforating sheet metal or other thin materials with a complex hole pattern.

[5] Human effort would still be required for programming, repairs, maintenance, purchasing, general management, guard duties, vendor inspections, etc.

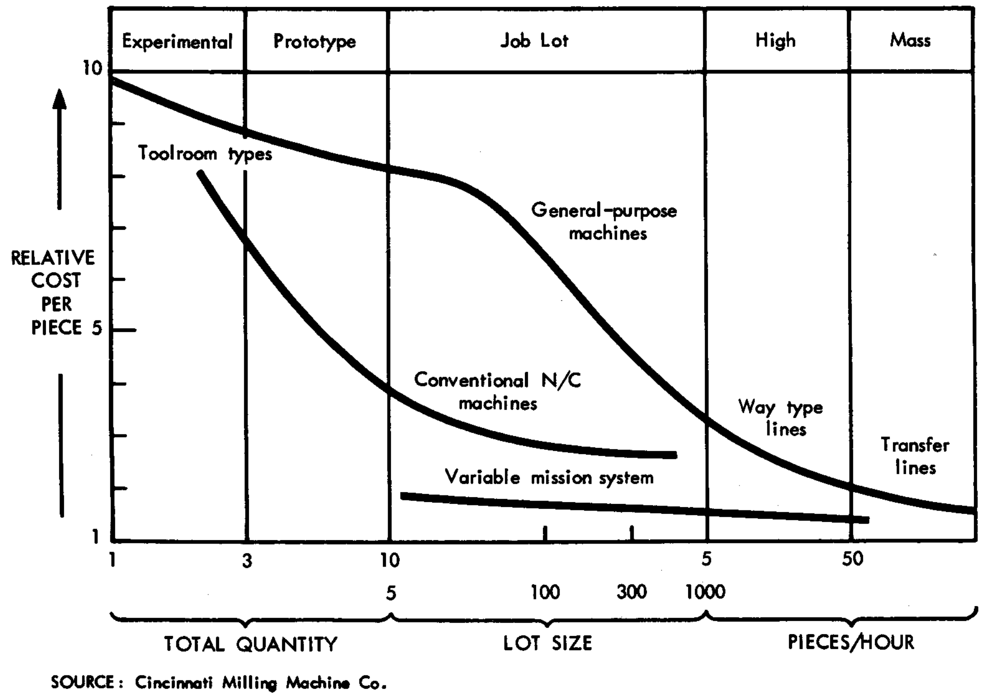



Fig. 2—Machining systems cost trends

components into a *unified facility* in which parts forming, machining, assembly, inspection, transfer and storage of materials, and scheduling are all (1) *highly automated,* requiring little personal intervention (and therefore not dependent on human reaction speeds or human variability); (2) *flexible,* so that the same process can be used to manufacture diverse items within a product class[6] and design changes can be easily accommodated; and (3) *highly integrated* with computer-aided design and engineering facilities, accounting systems, and management information and control systems, providing rapid acquisition and assimilation of information from each of these areas.

By altering computer programs and data bases in such a system, the processes they control (such as machining, inspection, assembly, scheduling, and material storage and transport) can be altered to produce new products (within a product class) or variations of existing ones. The tools and processes required in a programmable-automation facility must be highly flexible; for example, a system might include N/C machine tools with automatic tool-changing means.

## HARD VERSUS FLEXIBLE AUTOMATION

There are fundamental differences between programmable automation and the traditional notion of automation characterized by "Detroit-style" mass-production

[6] An example of a *product class* would be small electromechanical systems, including such items as electric typewriters, tape recorders, guided missiles, and avionics subsystems.

techniques. This "hard" automation is used in operations with very high rates of production, where complex but inflexible machines accomplish a few tasks on a single product at great speed. When the product changes, these machines must usually be discarded and new ones designed and purchased. For somewhat lower rates of production, semihard-automation machines are more practical. When the product changes, these can be mechanically reconfigured; however, this may require from several days to several months, and often many dies and fixtures must be stored until the same product is run again. Computer-programmable automation, on the other hand, would be applicable to lots of varying size and varying requirements, with production rates extending from the manufacture of a single prototype to rates at which hard automation becomes more economical. When the product is changed, programming and materials-acquisition time will be the principal elements in the system's start-up time. The required programming can, to a large extent, be done off-line.

One final difference between hard and flexible automation is that in hard automation, sensors are seldom used as feedback elements in closed-loop control systems. The flexibility of programmable automation is enhanced by the use of digital or analog servo systems, with sensors that measure displacement, force, pressure, reflectivity, and electrical or other characteristics. Hard automation, when it does employ sensors, uses them in an open-loop manner to accept or reject a part or an assembly.

## PURPOSE OF AND APPROACH TO THIS STUDY

The study presented in this report was performed by an interdisciplinary team encompassing skills in software systems, artificial intelligence, computer hardware and sensor technology, manufacturing engineering, automation, and economic analysis. Members of this team inspected over thirty manufacturing firms, including most major machine-tool and industrial-robot manufacturers, and had extensive contacts and discussions with computer-science researchers in universities and non-profit institutions. (Appendix A lists the persons interviewed and organizations visited.) As the discussions progressed and the importance of individual elements of programmable automation became increasingly evident, the study team pursued the following approaches:

1. To provide a focus, we restricted our examination to an automated factory that we assumed to contain processes suitable for the production of a broad class of electromechanical products of some complexity, as defined in Fig. 3.
2. A conceptual model of the factory and its elements was created.
3. Each element was examined for technical feasibility.
4. As a test case, the capital investment required for a programmable factory, capable of producing small antitank missiles at the rate of 600 per month, was estimated and compared with the capital costs for a conventional facility.
5. The operating costs for producing a small missile in the model factory were estimated and compared to current costs for conventional manufacture of the same missile.

The feasibility of advanced computer-based automation cannot be determined simply by considering the piecemeal automation of each isolated component of the traditional manufacturing process. The entire manufacturing process must be reexamined with regard to the flow of materials, the flow of information, the decision-

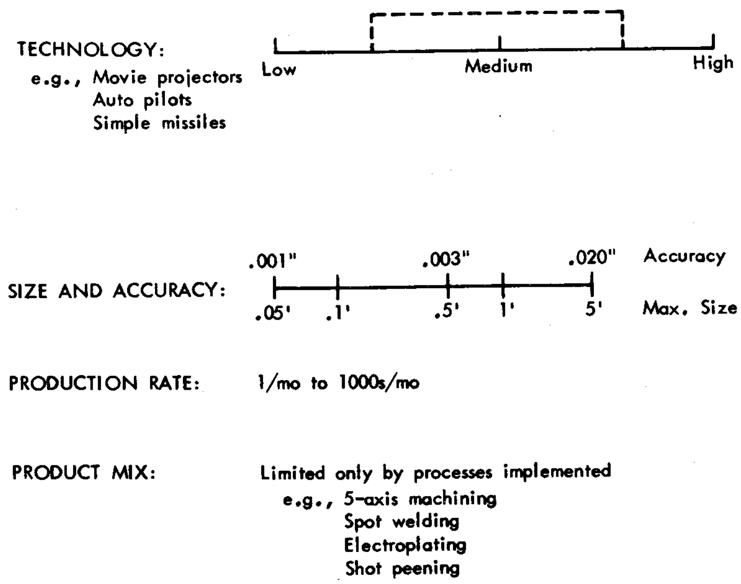



Fig. 3—Assumed automated-factory characteristics

making process at several levels (e.g., operation control, management control, strategic planning) [9], product design for automated manufacture, and the required flexibility in the entire process. The point is well stated by John Diebold:

> Not only does the approach of mechanizing *present* operations fail to yield the most efficient solution to the task at hand, but it often leads people to think of certain operations as entirely inappropriate to automatic control when in fact the opposite may be true. By contrast, rethinking of automation problems, involving redesign of the process, the product, the machinery, or perhaps all three, may produce results even greater than anticipated. [10]

Feasibility is significant only if the potential benefits outweigh the costs, both economic and sociologic. On the other hand, an analysis of the benefits depends heavily on technological and economic/sociologic assumptions, and such an analysis is desirable only if the concept seems feasible. The interdependence of these factors requires an iterative approach to the problem: a preliminary technological-feasibility and cost-benefit analysis of an initial technological-automation concept; revision of the concept on the basis of the analysis; reanalysis of costs and benefits. The necessary detailed analysis was beyond the scope of the present study; however, future studies based on this approach will need to be performed in order to develop a technologically sound concept of programmable automation that will significantly benefit both the DOD and the U.S. economy.

# II. A MODEL OF AN AUTOMATED FACTORY

To consider the technological feasibility of the progammable-automation concept, we examined various possible hardware configurations of tools, transport mechanisms, etc., which met the criteria of being highly automated, flexible, and highly integrated.

Figure 4 shows one possible factory configuration that resulted from that examination. Work stations consisting of machines or processes are positioned at standard gridpoints, with power and information resources available at each gridpoint. The work stations are grouped according to function (shaping, assembly, test, inventory) to simplify maintenance and scrap removal and to optimize environmental conditions, such as cleanliness, for each function. A random-access conveyor grid, either floor- or ceiling-mounted, is used to route materials or subassemblies between any two work stations under direct computer control. The process or machine at each work station is under direct computer control (with closed-loop feedback where appropriate) and is programmable to the extent necessary.

Figure 5 shows in more detail a preliminary concept of the interface between the conveying system and the work stations. An industrial robot, similar to those commercially available today, might be used as the interface between several work stations and the conveyor. Orientation of parts and subassemblies is maintained throughout the process.

The configuration shown in Figs. 4 and 5 provides the following advantages:

1. Several different products (within a particular product class) can be manufactured simultaneously using work-station resources in common. The scheduling of resources and transport of materials to meet these requirements is performed by a programmed scheduling algorithm.
2. New processes or machines can be introduced into the facility at available gridpoints without disrupting existing production. After these new facilities are debugged and become available for use, the scheduling algorithm merely alters the routing schedule accordingly. This flexibility allows the manufacturing facility to expand and to be resilient to changes in materials or processes caused by technological change.
3. Use of the same work-station facility for several distinct steps in the manufacturing of a product can reduce the capital cost required for that product's manufacture.

This illustrative factory configuration represents only one stage in an iterative analysis cycle (concept formulation)(benefit/cost estimation)(concept revision). Nevertheless, it forms a useful initial framework within which the feasibility of programmable automation and preliminary cost/benefit analyses can be explored.

For this investigation, we assume that it is technologically feasible to build a machine (or write a computer program, etc.) meeting given specifications, as long as the design of that machine or program can be based on existing technology, using known components and processes, so that its successful construction can be predicted at the conclusion of a well-defined development program. Such predictions are, of course, fallible. Since a primary goal of this study is to obtain indications of feasibility, our considerations should include the prognosis for success for each required development program. Also, we must specify the goals of the development programs, along with time estimates for their completion.

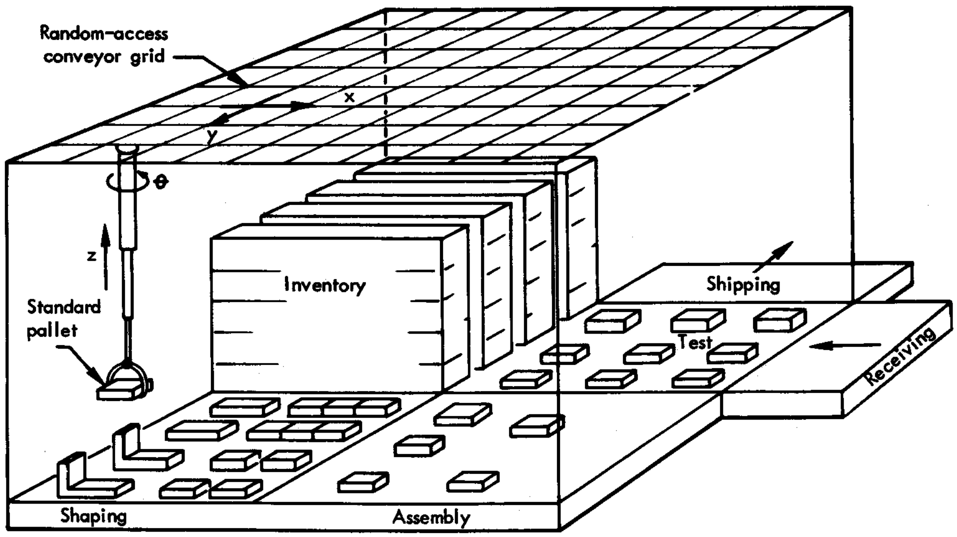



Fig. 4—An illustrative automated-factory configuration

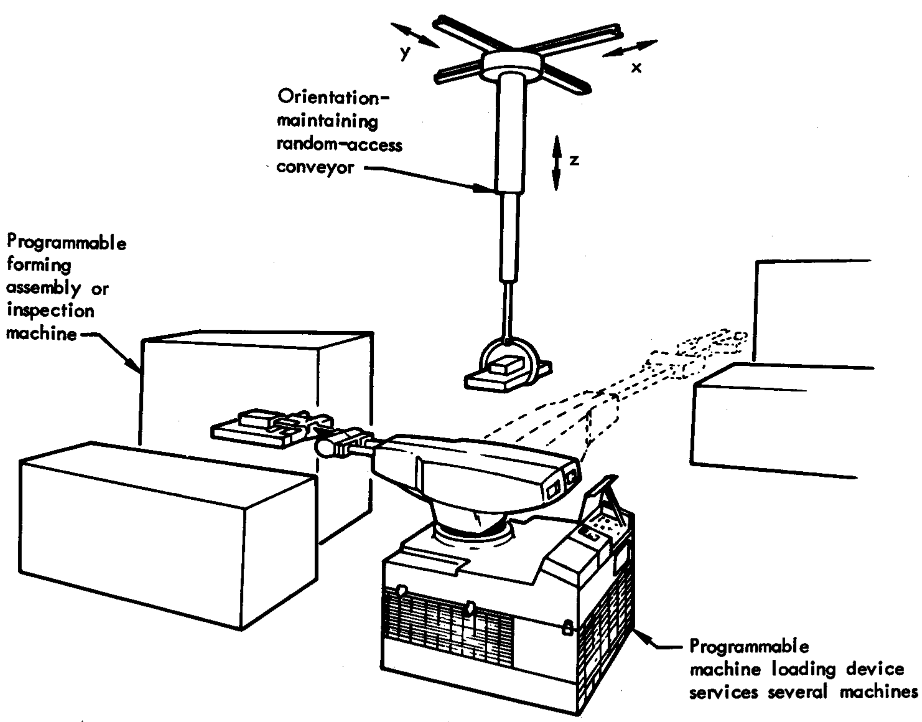



Fig. 5—A preliminary concept of programmable components

The major components of an entire manufacturing firm employing the programmable-automation concept (including software, management, and control, as well as the hardware shown in Fig. 4) are shown schematically in Fig. 6. For each component we will contrast the methods and machines found in typical industrial environments today with those that would be required for the programmable-factory model.

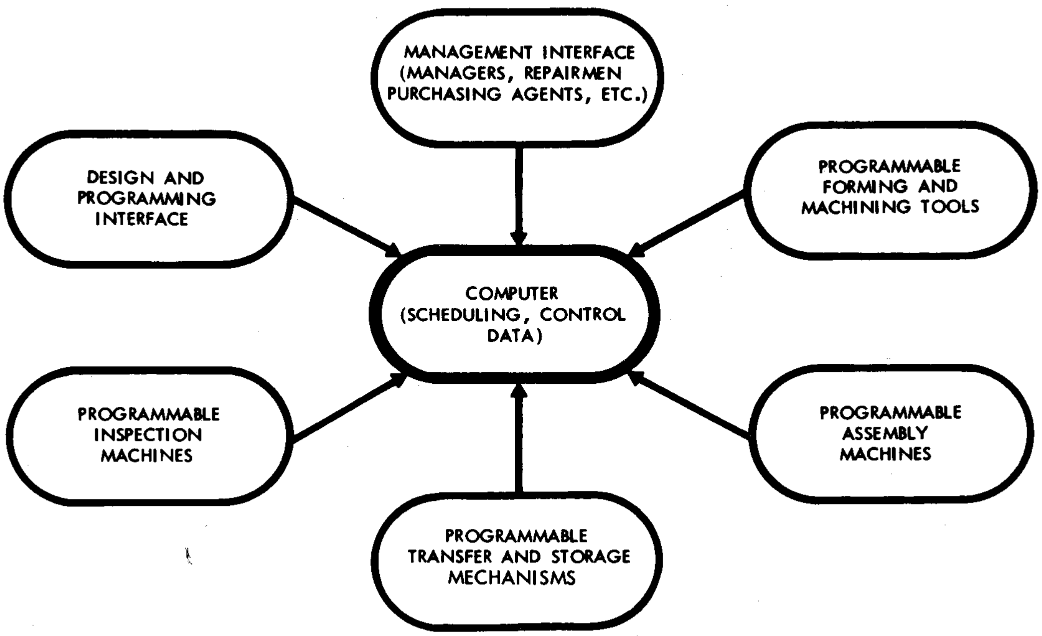



Fig. 6—Major components of a programmable-automation manufacturing firm

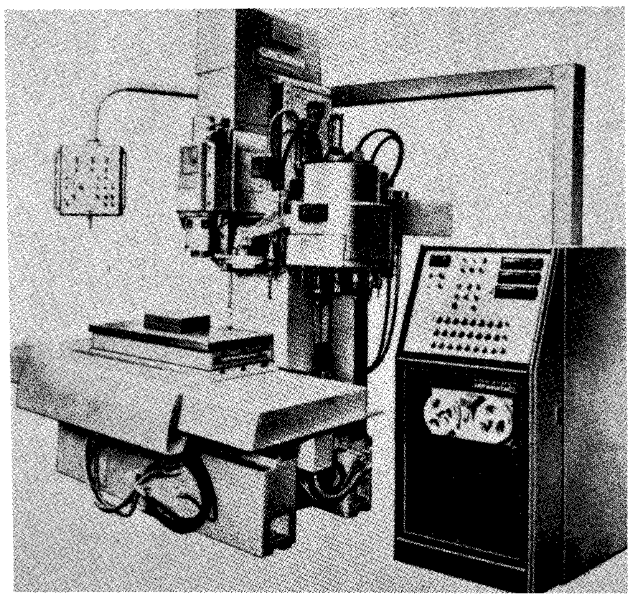
## MATERIAL-SHAPING TOOLS

Numerical control of machine tools has been a reality since the mid-1950s. These N/C tools were initially mainly metal-cutting tools—drills, milling machines, and lathes. The industry has since progressed to multiaxis, multiple-tool machines under direct computer control, such as Kearney and Trecker's System Gemini or Sundstrand's Omni-Control. The types of N/C machines available today include grinders, punches, shapers, planers, and other metal-cutting and some forging tools. Generally, machines that shape softer materials—plastic, wood, etc.—have not been widely subject to numerical control. These are either manually operated, tracer-following, or hard-automated with metal dies that can be (but usually are not) produced on N/C machines.

Figure 7 illustrates a conventional, stand-alone N/C metal-shaping tool, which is loaded and unloaded by hand; the advanced version shown is System 24 of Molins Machine Co., Ltd., of London [8], a computerized system for the batch production of small machined parts, comprising several N/C tools linked by a conveyor system. The tools are capable of automatic loading and unloading of palletized parts [11].

CONVENTIONAL

Stand-Alone N/C
Tool and Director



ADVANCED

Direct N/C (no director)
Adaptive Control (not illustrated)
Self-Testing (not illustrated)

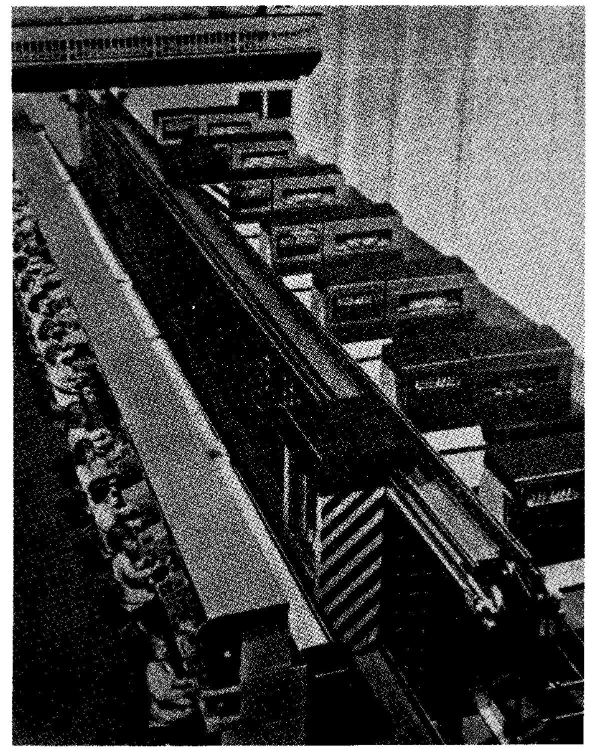


Fig. 7—Material-shaping techniques

Even though the Molins system lacks many of the elements of a fully automated factory, its economic advantages over conventional systems are expected to be spectacular. The Molins economic forecast is shown in Fig. 8 (from Ref. 8).

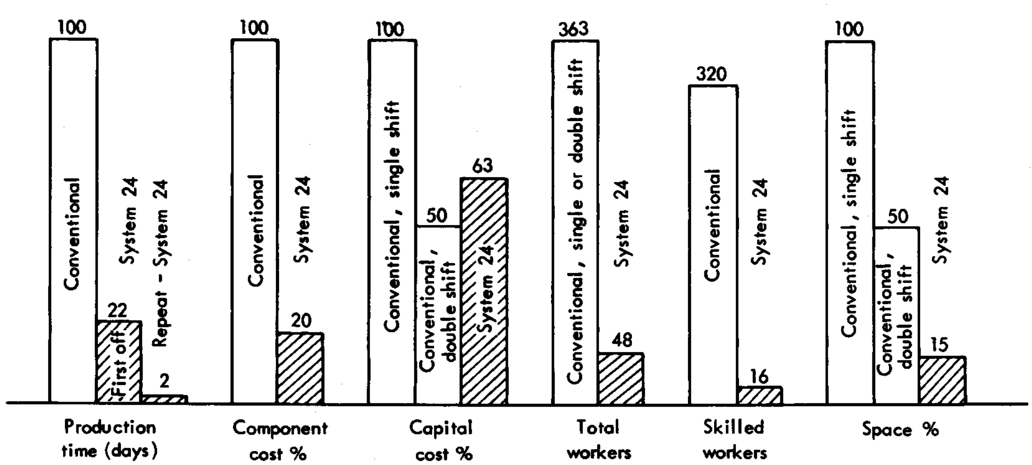
It should be emphasized that System 24 is a parts-fabrication process, not a manufacturing process for a complete and complex product. Furthermore, it falls short of complete computerized automation on two counts:

1. It lacks self-testing features for actual or incipient machine failure.
2. It does not have flexible adaptive feedback.

These shortcomings are taken into consideration in the recommended development program discussed in Sec. IV.

Numerically controlled machine tools are off-the-shelf items in today's technology. The development of self-testing features, which would inform the central computer of conditions such as tool wear, tool breakage, or motor overloads, is certainly feasible over the next several years.

Similarly, adaptive feedback has been demonstrated (e.g., by The Bendix Corp.), but only for single-tool machines; nevertheless, it would require relatively little development effort to perfect. In adaptive feedback, local sensors determine whether the cutting tool should remove metal more rapidly or less rapidly than computer instructions call for, in response to indirectly measured variations in material density and cutter sharpness. There is some question as to the overall advantage of adaptive feedback because of the large number of optimization algorithms required to accommodate the great variety of existing material and tool characteristics. Again, the tradeoffs have not been determined as to what is economically most advantageous in the overall progammable-factory milieu.




Note: "Conventional" refers to manually operated machine tools. Component cost, capital cost, and space are all based on taking the conventional system as 100.

Fig. 8—Comparison of Molins System 24 characteristics and capabilities with those of conventional (manually operated) machine tools, machine-loading and unloading techniques, and intermachine parts conveying

There is still another area, and a very large one, in which sensory feedback may have valuable application: the area of machine-tool design. Current designs call for massive and highly rigid construction to minimize the effects of deflection and vibration. Theoretically, machine tools might be built with much less mass and rigidity if sensory feedback could be used to compensate for deflection and vibration. We only mention the subject here, as it is not essential to the technical feasibility of a programmable-automated factory. Existing tools will do the job, with the exceptions noted above.

## WORK-HOLDING FIXTURES

Whenever a machine performs the operations of forming, assembly, or testing, the object worked upon must be rigidly supported in a known position relative to the machine. Today's factory uses a wide variety of specially shaped metal, wood, or plastic devices to accomplish this function. These devices are usually referred to as work-holding fixtures and are usually designed to hold one specific product at one specific stage of manufacture. The production of fixtures for each product represents a sizable manufacturing and storage cost and contributes heavily to the start-up time lag.

In our model of a programmable factory, we have assumed certain dimensional and accuracy limits for work-holding fixtures. It is conceivable that programmable fixtures could be developed to hold objects having common geometrical shapes, such as right circular cylinders, right circular cones, frustums of right circular cones, pyramids, frustums of pyramids, segments of spheres, circular tori, wedges, frustums of wedges, segments of ellipsoids and paraboloids, and a variety of rectangular parallelepipeds. Whether these shapes could be supported in the desired positions and in a manner that would not interfere with the operations to be performed is open to question. Also unsolved is the problem of programmable fixtures for more complex or arbitrary shapes.

As a base position, fixtures could be produced for each step of the manufacturing process as they are now, by separate design. Most likely, a programmable manufacturing system could produce fixtures as well as products. The ability to produce special-purpose fixtures by today's methods is assured; making programmable fixtures will require development effort and ingenuity.

## MACHINE-LOADING/UNLOADING DEVICES

Machine-loading/unloading devices like the one depicted in Fig. 5 provide a necessary interface between a rather inaccurate conveyor system and machines that require fairly accurate work loading and unloading. Work-transfer devices, such as those made by Unimate, Versatran, and a score of other producers, should be able to perform this task at reasonable cost. Although these machines exist, they have not been very flexibly programmed; however, that appears to be a relatively simple development.

## ASSEMBLY MACHINES

In very high-rate production, assembly machines may be used to accomplish a few tasks on a single product at great speed. These machines usually must be

replaced when the product changes. Somewhat lower production rates call for assembly machines that can be reconfigured and retooled by mechanics when the product changes. Such reconfiguration may require from several weeks to several months.

It has been estimated that nearly 80 percent of U.S. goods are produced at moderate production rates [7]. These goods are manufactured by job shops (or batch producers), where assemblies are varied and change is frequent. These moderate rates of production cannot economically support either of the above-described automatic assembly machines, so assembly is typically performed manually, as shown in Fig. 9. The programmable factory will require a computer-programmable assembly machine that is as universal as possible. It must be capable of accommodating many part shapes and sizes and a broad spectrum of joining methods.

As far as we know, no such machine exists. Yet the basic problem does not seem insoluble, given the current state of the art of robotics [12,13,14] and teleoperator projects [15]. Fundamentally, the assembly process consists of a few simple but precise steps, involving two parts and a method of joining them. The requirements are:

1. Part A must be supported by the machine in a known attitude.
2. Part B must be supported by the machine in a known attitude relative to Part A.
3. Part B must sometimes be cemented, drilled, etc., in preparation to being joined with Part A.
4. Part B must be manipulated (press-fitted, screwed, etc.) so that it is joined to Part A.
5. Other means of fastening (riveting, spot welding, pinning, electromagnetic shrink fitting) may have to be used to provide a bond between Parts A and B.

These are the basic assembly operations, whether one is producing a locomotive or a Swiss watch. However, a single assembly machine obviously would not be appropriate for both the watch and the locomotive.

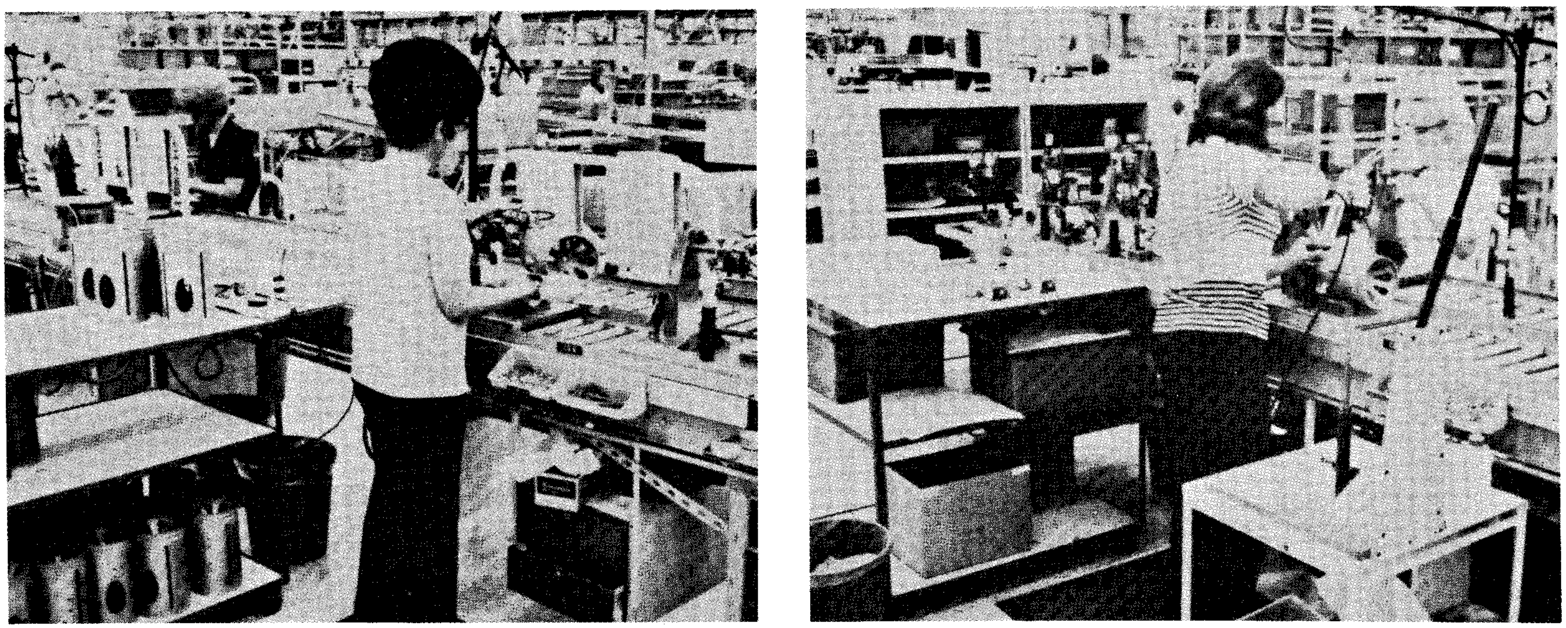
It is clear that automated systems will require that product-design methods be redirected to take maximum advantage of operations in which assembly machines excel (just as designs are currently directed at human assembly). For example, it may be more efficient to mount small parts on other parts by cementing [16] rather than by drilling, tapping, and screwing.

Robots, as they currently exist, are not useful in the performance of most assembly operations. Current robot accuracy of p.010 to p.060 in. is far from sufficient to carry out most assembly tasks, even when the robots are equipped with tactile sensors, due largely to the appreciable deflections imposed by a load on the various members. We have examined the eye-hand machines being developed by several groups and have omitted them from consideration here because they are very costly (the required computer memory is particularly expensive) and do not make use of all the available information. What appears to be needed are assembly machines that have the rigidity and hence the precision and repeatability of machine tools and that take advantage of known dimensions and orientations. Since the forces dealt with during assembly are usually considerably less than those to which cutting tools are subjected, assembly machines need not have the bulk and weight of cutting machines to achieve the same rigidity. We believe the art has advanced to the stage where a focused development program can lead to the production of a class of general-purpose programmable assembly machines, each optimized for a range of sizes, tolerances, or fastening operations.

OPERATIONS

MOVE FIXTURE A 90°
SLIP CENTER SECTION OVER FIXTURE A
ORIENT CENTER SECTION ON FIXTURE B
DRIVE 8 SCREWS

2 WORKERS
2 FIXTURES
1 POWER SCREWDRIVER
200 $ft^2$ SPACE
CIRCA 4/HOUR



Fixture A - Supports Gyro-Battery Assembly
Fixture B - Orients Center Section

Fig. 9—Conventional (manual) assembly operations

To evaluate in some detail the feasibility of general-purpose programmable assembly machines, we have analyzed the machine assembly operations (excluding electronics subassembly packages and final munitions loading and packaging) for a small missile. We have concluded that, with some allowance for product redesign to accommodate automated assembly, a programmable machine such as that shown in Fig. 10 would be capable of performing most of the required intermediate mechanical assembly operations at an operating-cost saving of 50 to 75 percent. This machine is designed for classes of products with cylindrical symmetry; other classes of machines could, of course, be designed for rectangular products in an analogous manner. Through such design exercises, we have become convinced that flexible, programmable, automated assembly machines are generally feasible and that they would be vital components of a flexible, automated manufacturing facility.

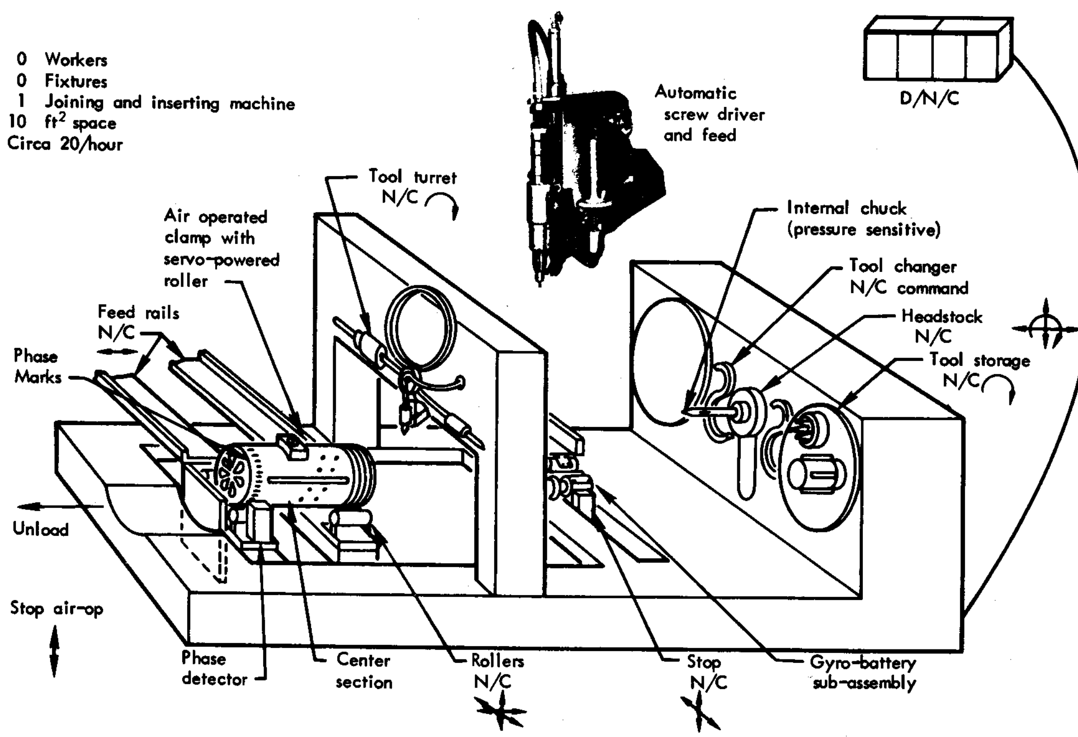



Fig. 10—Advanced programmable assembly machine

## TRANSFER AND STORAGE MECHANISMS

In the illustrative programmable automated facility shown in Fig. 4, the overhead conveyor and the floor-mounted machine and storage elements conform to an x-y grid location. The conveyor is computer-programmed and able to move from any x,y,z coordinate set to any other x,y,z coordinate set. In addition, the conveyor provides a rotation in the $\Theta$ direction (i.e., in the x-y plane) so as to present a part or assembly to a machine or storage area with the correct orientation. Many conveyors would be in operation simultaneously, with optimum noncollision paths com-

manded by the central computer. To our knowledge, no existing conveyor system is as completely computer-controlled or as flexible as this one. The development needed for the fully automated system appears to require no new technology, however, and should be easily accomplished in a few years.

Automatic warehousing, on the other hand—for tooling, parts, and work in process—is a well-advanced art. Rohr, Harnischfeger, and Burch are among the many companies producing highly automated warehouse systems. Yet, automated warehousing techniques are not commonplace in the U.S. manufacturing industry today, and the type of computerized material transfer described above is nonexistent. There is, typically, heavy reliance on bins, boxes, or pallets (containing parts) moved by forklift trunks or handcarts, as shown in Figs. 11 and 12, and manual or crane machine loading and unloading from these.

## INSPECTION MACHINES

The mechanical requirements for programmable inspection machines are similar to those for general-purpose assembly machines. The inspection machine holds a probe or sensor, instead of a screwdriver, in its "hand." Economical inspection depends on the development of a uniform family of sensor interfaces and minimal data-processing requirements. A uniform software interface to the variety of sensors required is desirable to minimize the programming task for interpretation of sensor signals. Most inspection steps in a manufacturing process do not require pattern interpretation or other complex techniques; they generally provide yes/no or single-variable signals. Thus the programming interface should be quite manageable. The current range of sensing and testing techniques used in manufacturing is given in Appendix B. As shown, there is no lack of sensors.

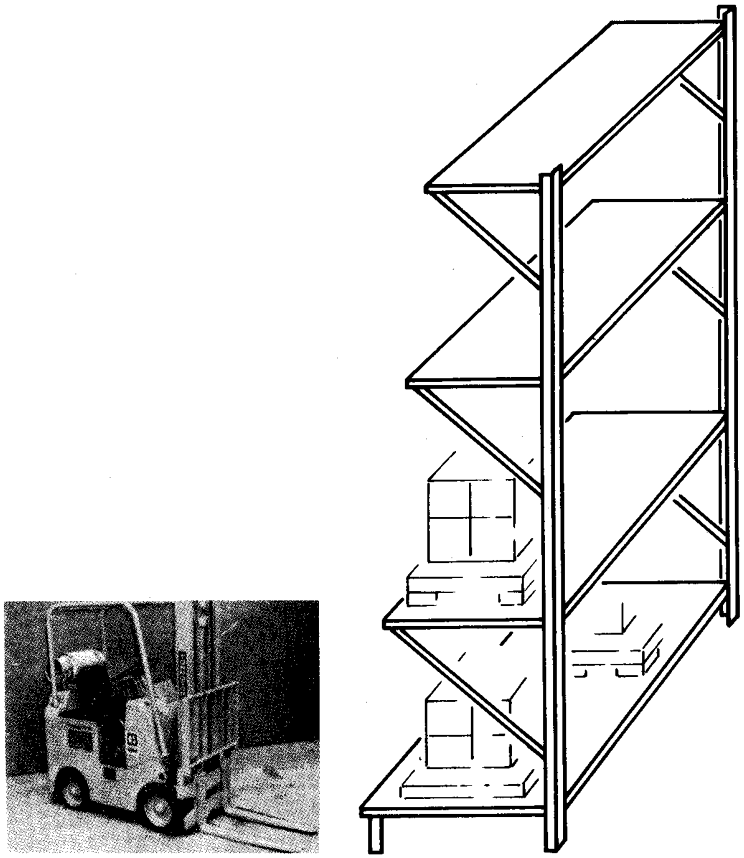
Figure 13 illustrates the replacement of manual pattern comparison by computer-controlled pattern analysis. Specific detailed measurements and comparisons can be computer-controlled in a rather straightforward manner. However, it has been difficult for us to determine the extent to which "casual" inspection is performed by workers during the manufacturing process and to what extent such detection of unforeseeable and global errors is vital to the success of the process. Currently, most faults during manufacture are related to human error, and since the possibility of human error will be drastically reduced in a highly automated facility, the ultimate burden on the inspection function can only be known when a prototype facility is in operation. Otherwise there appears to be no bar to the technical feasibility of programmable inspection and test, and informal inspection could still be accomplished by a few human overseers.

## THE DESIGN AND PROGRAMMING INTERFACE

In the totally programmed factory, characterized by independent manufacturing elements interwoven by a conveyor system, the flexibility of the factory resides in the programming system used to control it. If the programming system is unwieldy and inflexible, the factory also will be inflexible.

The programming system must control a wide variety of activities. The activities may be routine, day-to-day operations that require initial programming and intermittent maintenance, such as those of the basic computer operating system, the inventory reporting and control system, and various scheduling and work-center

CONVENTIONAL



ADVANCED

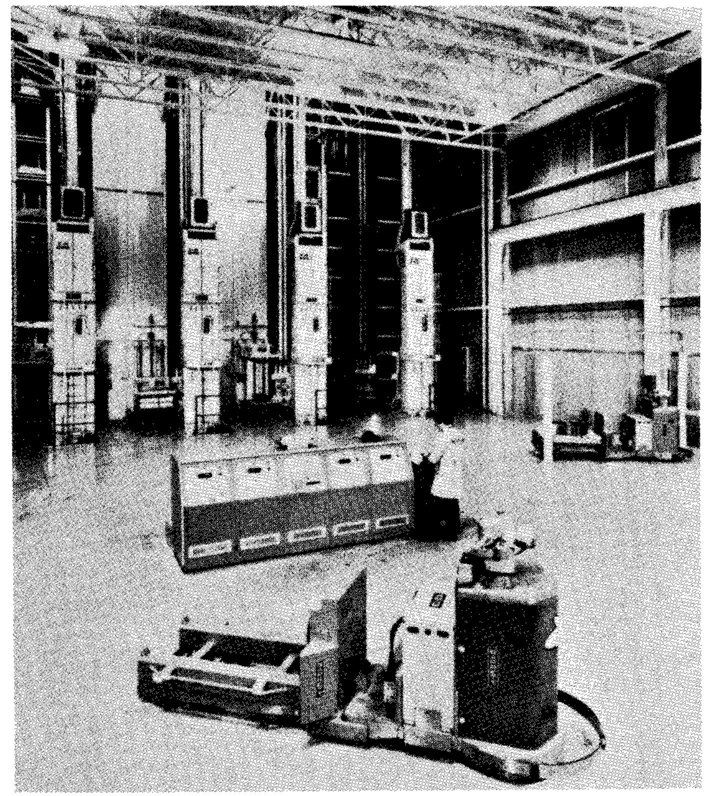


Fig. 11—Storage techniques

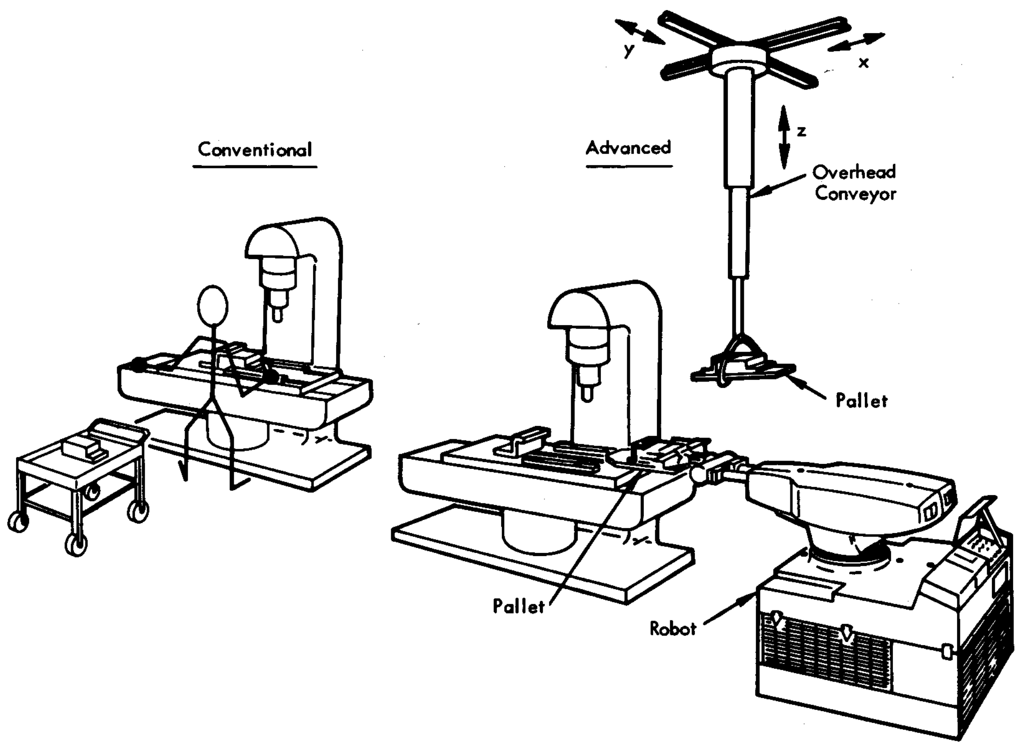



Fig. 12—Material transfer and machine-loading techniques

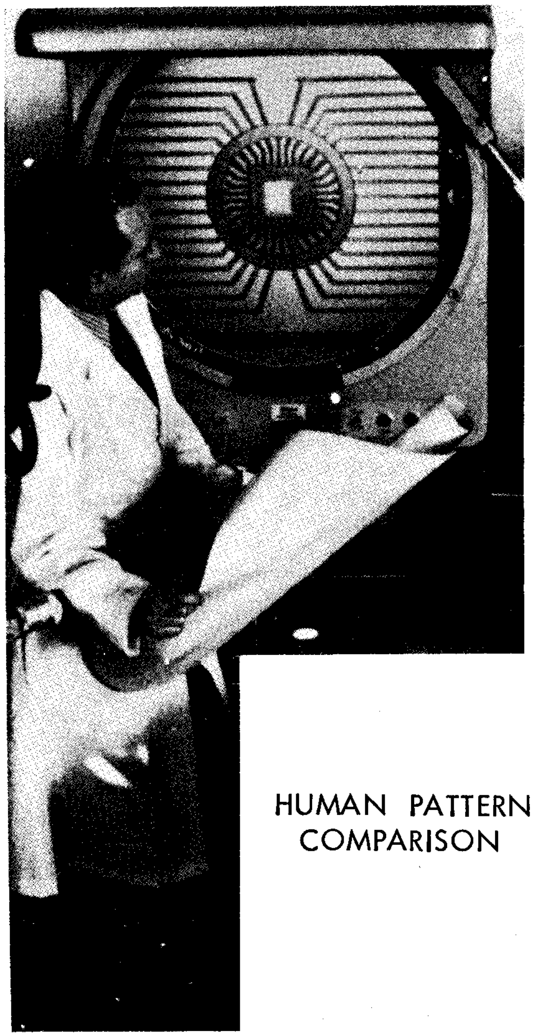
loading algorithms. Alternatively, the activities may be highly variable and unique, for example, the fabrication, assembly, and testing of a new product.

The routine operations require a compact, efficient computer code yet must be programmed and maintained easily, calling for a well-thought-out systems programming language and an efficient compiler for that language. Corbato produced a large-scale time-sharing system using such a language [17], and a survey in the SIGPLAN Notices of October 1971 covers other such languages. Also, the programming system can be designed in such a way that changes in products and product mixes result in changing only isolated program modules and parameters but not in massive reprogramming.

Advanced on-line computer techniques (Fig. 14) would provide the basis for programming the unique and variable activities of the automated factory. These techniques use a special language such as APT, a language for programming N/C tools [18], which is representative of a class of languages that can be used to control mechanized fabrication, assembly, and testing. Extensions of APT, using computer graphics [19,20,21], provide a highly effective programming tool. In addition, industrial robots such as the Unimate and Versatran can be programmed by leading them through the required motions, although these machines currently lack the accuracy required for such tasks [22,23].

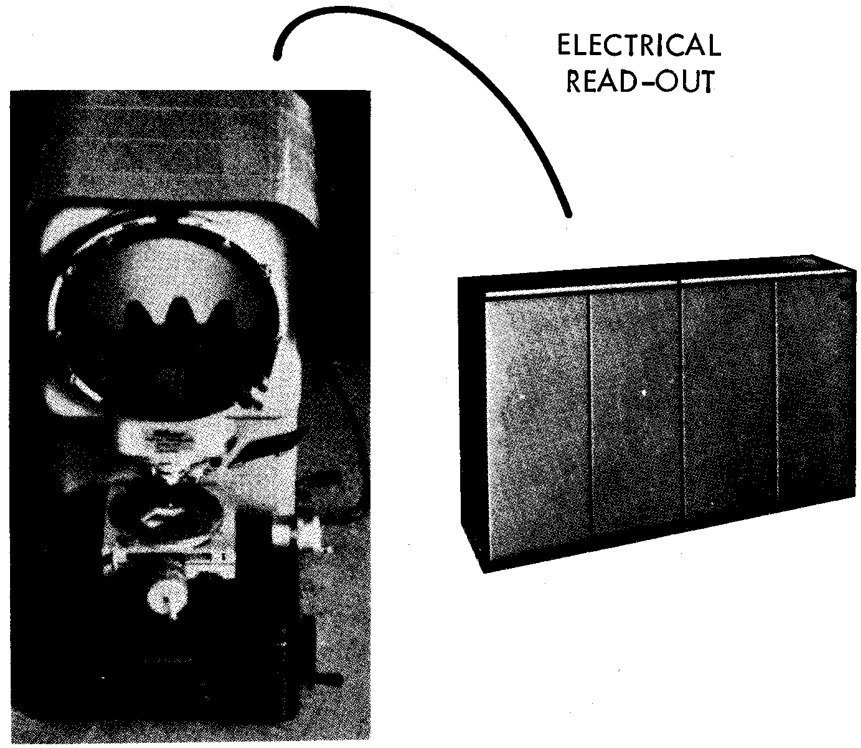
Because of the bulk of the programming and data-entry effort required, the design, prototyping, and production-engineering phases of the manufacturing process must be an integral part of or at least completely compatible with the automated

CONVENTIONAL



HUMAN PATTERN
COMPARISON

ADVANCED



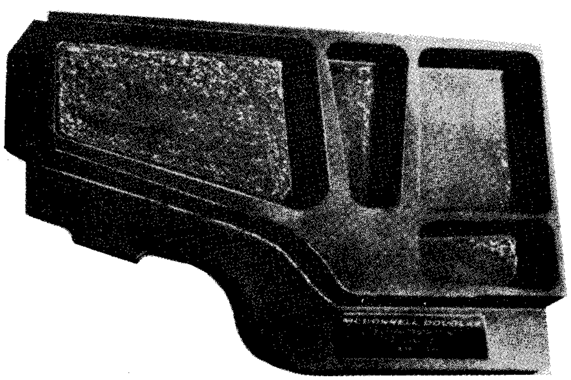

COMPUTER-CONTROLLED
PATTERN ANALYSIS

Fig. 13—Inspection techniques

CONVENTIONAL

84 HR —BLUEPRINT TO TAPE

PLANNING
APT PROGRAMMING
2.5 CORRECTION CYCLES
PLOT PROOFING
TOOL PROOFING



ADVANCED

(McDonnell-Douglas, St. Louis)
4 HR —BLUEPRINT TO TAPE

PROGRAMMING WITH ON-LINE COMPUTER GRAPHICS

Fig. 14—Programming processes for numerical control

facility [24,25]. (They need not be physically integrated, but they must be able to contribute to the information flow within the facility.) For example, properties of materials such as tensile strength and ductility must be known to the designer when he specifies thickness of supporting members, etc., in a part design; those same properties are used in the programming of an N/C tool to determine feeds and speeds appropriate for cutting that material. Material properties and other similar information should have to be entered only once into the information system governing the facility; the information should then be available to all components of the manufacturing process requiring it. (The collection and computerization of such information are presently under way in Europe [26].) Similarly, information originating on the factory floor during the manufacturing process must be available for the management and scheduling decisionmaking process, regardless of whether that process is performed by humans or by computers.

## COMPUTER COORDINATION OF PROCESSES

The coordination of the various processes within a manufacturing firm is traditionally a function of management. The management-decision structure we have assumed for our automated-factory model was described by H. A. Simon over a decade ago:

> Organizations will still be constructed in three layers, an underlying system of physical production and distribution processes, a layer of programmed (and probably largely automated) decision processes for governing the routine day-to-day operation of the physical system, and a layer of non-programmed decision processes (carried out in a man-machine system) for monitoring the first level processes, redesigning them, and changing parameter values. [27]

We will not discuss here the province of top management except to consider possible man-machine systems. The lack of understanding of the problems in this area has caused many management information systems to founder. Such complex factors as the political climate, the anticipated behavior of the economy, and the effects of new markets are beyond the scope of the present study.

Simon assigns the day-to-day routine decisionmaking to the realm of operations research. Managerial functions such as inventory control, operation scheduling, requirements planning, and capacity planning must either be automated or made available through a man-machine system [27]. Software products have already been developed which cover much of this ground, for example, IBM's PICS [28], shop floor control [29], capacity planning [30], and inventory control [31]. Moreover, recent publications provide an extensive framework for planning factory computerization [32].

It is not yet known whether all of the required activities in a manufacturing facility can be initiated and controlled automatically (or semiautomatically) and in concert. Of course, no single manufacturer encompasses all the functions we have discussed, but there are many examples of partial steps in that direction. Black and Decker's overall logistics system consists of "intricate integrated packages of separate subsystems interfaced with one another." Individual segments operate independently but are interrelated through the use of a common data base. The original Black and Decker concept was formed in late 1966 [33].

Another important coordination function is that of self-testing and diagnosis of faults within the manufacturing process, combined with procedures for automatic

reactivation of the facility in the event of failure. Reactivating a factory is quite different from reactivating a computer program. Many physical processes cannot be interrupted and then restarted without special recovery procedures. Even if human intervention were available to aid in the recovery process, the flow of materials and information within an automated firm could well be too complex to be understood by humans at the micro level; human judgment in the recovery process must be augmented by the problem-solving ability within the central computer controlling the manufacturing process. Although this subject is presently not well understood, it appears that human intervention (at some level) will be required in the automated factory.

# III. THE POTENTIAL IMPACT OF PROGRAMMABLE AUTOMATION

The general impact of programmable automation on the DOD would probably be similar to its impact on the civilian economy; the possible differences would result from the DOD's greater sensitivity to lead time or production start-up time problems under certain conditions (e.g., during a shooting war). The principal potential impacts that we foresee are listed below:

*Economic Impacts*

1. Reduced manufacturing costs for batch lots of assembled products, and reduced tooling-up costs.
2. Reduced initial capital investment requirements, especially for new plants.
3. Lower inventory costs.
4. Greater product uniformity and reliability.
5. Shorter lead time for new products or engineering changes.
6. More economic and speedier product innovation.
7. Substantially increased productivity.

*Social Impacts*

1. Elimination of hazardous, boring, and repetitive manual tasks.
2. Upgrading of the manufacturing work force.
3. Increased possibilities of geographic decentralization of indutries, e.g., to noncongested outlying areas.
4. Temporary dislocation of certain skills, until retraining is accomplished.

Although no *detailed* analysis of the expected benefits of programmable automation is possible at this time, we have developed some rough estimates of these benefits based on the data available in the literature [34], manufacturers' estimates of the operating characteristics of advanced equipment, information gleaned from interviews with cooperating industrial personnel, and expert opinions. These estimates should be regarded as a preliminary attempt to describe the midpoints of a set of distributed outcomes exhibiting substantial variability. However, the initial analysis indicates that the expected benefits from programmable automation could be very substantial. Some of our estimates of these benefits are shown in Table 2 and discussed below.

## ESTIMATED COST AND TIME SAVINGS FROM PROGRAMMABLE AUTOMATION

### Manufacturing Costs

According to published estimates and interviews with industrial personnel, 50 to 75 percent of the direct labor costs in the production of discrete engineered products are attributable to assembly operations, with an additional 10 to 20 percent attributable to machining and another 25 to 40 percent to test and inspection operations. Machine-tool manufacturers have estimated that advanced machining

Table 2

ESTIMATED POTENTIAL BENEFITS FROM PROGRAMMABLE AUTOMATION

| Item | Reduction Due to Automation[a] |
| --- | --- |
| Manufacturing costs | 1/4–1/2 |
| Direct labor | 1/8 |
| Overhead labor | 1/2 |
| Engineering change | 1/3 |
| Scrap and rework | 1/3 |
| Capital-investment costs | 1/2 |
| Inventory costs | 1/4 |
| New-product tooling costs | 1/8 |
| Throughput time | 1/9 |

[a] Fraction of expense with fully automated operation, compared with conventional operation, i.e., using N/C machining only.

systems can reduce the direct labor associated with metal cutting to one-eighth of its present level. Fully automated assembly machines would replace at least as great a proportion of direct labor in assembly functions, inasmuch as conventional assembly operations are typically performed much less efficiently than conventional machining operations. Similarly, it appears that most test and inspection operations could be performed by current-state-of-the-art sensors, coupled with work positioners that would require more extensive development effort. At the same time, it may prove most economical to perform certain other functions with human interaction. On balance, then, an overall reduction in direct labor to one-eighth of the level in a conventional factory appears reasonable, as the machine-tool manufacturers' estimates assume a greater degree of human interaction in machining operations than is probably necessary.

Industrial interviews indicate that one-half of the currently required overhead (i.e., supervisory) labor could be eliminated by software, automated materials handling, and automated inspection. Additionally, some overhead reductions could be expected as a result of the decreased size of the direct and indirect labor forces. A traditional rule of thumb calls for one supervisor for every 3 to 10 persons and one manager for every 3 to 5 supervisors. Many, if not all, of these positions would be unnecessary in a fully automated facility.

The cost of an engineering change in a programmable factory can be approximated by doubling today's cost of programming an N/C machine.[7] Present industrial experience indicates that the time required to go from blueprint to operation using conventional methods could be reduced by as much as 90 percent by the introduction of interactive on-line computer graphics systems. On this basis, a reduction in engineering-change costs to one-third of the conventional cost appears a reasonable preliminary estimate.

[7] Personal communication from H. Davis, Hughes Aircraft Company.

Most of the faults requiring rework or producing scrap in today's factories can be traced to human error on the part of the workers. Once automated machines are programmed and debugged, most of these errors would disappear (most programming errors would be detected earlier in computer simulation runs). Thus we have estimated that programmable automation would reduce scrap and rework costs to about one-third of their present level.

### Capital-Investment Costs

Comparative capital-investment figures for conventional and automated factories have proved difficult to estimate. Existing facilities are admittedly obsolescent by today's standards, and many, because of their age, are being utilized for a product or in a manner other than that for which they were originally intended. Moreover, most factories produce more than one product, making the separation of appropriate capital costs difficult. As a consequence of these and other factors, the capital-investment comparisons developed in support of this research must be considered only as speculative estimates.

We estimate that capital-investment costs for an automated factory would be substantially lower than those for a conventional factory. Because of increased machine-capacity utilization, automated operations require fewer machines than conventional operations. Also, elimination of most direct labor and many overhead activities would permit major savings in terms of the costs of land and buildings. Many conventional items such as forklifts, manual or semimanual work and material transport, and many personnel facilities would be eliminated altogether. These and other factors have resulted in estimates of 50-percent reductions in capital costs for a highly automated machine shop.

To provide an illustrative case, we attempted to compare the investment cost of an automated facility to produce small electromechanical missiles with the quoted reproduction cost of an existing factory. Our estimates are based on a detailed examination of the missiles and a preliminary industrial design of an appropriate fully automated facility for their production. Our estimate of the capital outlay for an automated facility that would produce such missiles at a rate of 600 per month was about $26 million. Equipment costs were calculated by comparison with presently existing equipment of comparable size and complexity. We assumed that the bulk of development costs would be underwritten by Federal support (as was the case with numerical control of machine tools) and that a comparable market exists for such automated equipment. A breakdown of our $26 million estimate is shown in Table 3. By contrast, executives of a conventional facility estimated a replacement cost of $80 million for their facility. Thus, a conservative estimate of the ratio of the investment costs of a conventional facility to those of an automated facility would be roughly 2 to 1.

### Inventory Costs

Isolated examples of highly automated, computerized inventory-control and requirements planning systems can be found at this time. Case histories of the introduction of these systems into existing facilities [35] show inventory costs reduced to about one-fourth.

Table 3

ESTIMATE OF CAPITAL OUTLAY FOR A PROGRAMMED-AUTOMATION FACILITY
(Small-missile production at a rate of 600 per month)

| Process | Equipment | Capital Cost ($ millions) |
|---|---|---|
| Shaping | 7 five-axis N/C tools, 4 two-axis N/C drills, 1 N/C grinder, 2 chemical finishing tanks | 3 |
| Electronic assembly | 2 assembly machines, 1 soldering machine | 1 |
| Assembly | 2 multiaxis N/C assembly machines, 1 N/C wire-wrap machine | 1 |
| Inspection | 5 multiaxis inspection machines, sensors | 2 |
| Transport and storage | Conveyors, stacking cranes | 1 |
| Control | 2 multiplexed large computers and auxiliaries, 1 large design and engineering computer | 4 |
| Scrap removal | Conveyors, machines | 1 |
| Plant and installation | 40,000 sq ft at $20 + installation | 9 |
| Subtotal | | 22 |
| Allowance for oversights | | 4 |
| Total | | 26 |

Note: The above estimates were arrived at, as follows:

1. Each step in the current manufacturing process was analyzed as to the function performed, parts required, and tests and inspections required.

2. An automatic production facility was postulated which performed the requisite functions.

3. The time required for each step was estimated and the number of machines required derived from this time and the desired production rate.

4. The initial cost of each machine was obtained from manufacturers, where possible, and were estimated from machines of similar function and/or complexity where the desired machine did not exist.

5. The manpower required was identified and the requisite space needed by machines and men was calculated, using industrial engineering principles.

## New-Product Tooling Costs and Throughput Time

The principal factors in the lengthy production start-up times in conventional facilities are:

1. Time required for tooling the facility for a new product, including many jigs and fixtures.
2. Slow initial deliveries from vendors.
3. Time required for hiring and training (or retraining) of production workers.
4. Throughput time.

In the case of the flexibly automated factory, tooling for a new product would be approximately equivalent to the programming effort. This effort would generally take considerably less time than the preparation of process drawings and instructions that are written for every worker in the manufacturing area (to ensure proper sequencing and completion of diverse operations), plus the preparation of conventional N/C tapes. Since scheduling in an automated factory is expected to be more

effective than that in a conventional facility, fewer machines or work stations would be required, with the attendant reduction in required fixtures. To the extent feasible, programmable fixtures would replace those especially designed and built for a particular step in a process.

Output of the first product is paced by the long-lead-time items. Unless the vendors furnishing the long-lead-time items also introduce automated equipment, significantly shorter lead times may not be attainable. If the vendors are automated, their own tool-up time and throughput time could be reduced to as little as one-eighth and one-ninth, respectively.

Machine-tool manufacturers have estimated that advanced machining systems can reduce machine-shop throughput time to one-fifth of its present level. As we have indicated, assembly, test, and inspection activities are considerably more time-consuming and considerably less efficient than machining activities. Indeed, a widely quoted rule of thumb suggests that a typical machine part is *not* being worked on 90 percent of the time it is in a factory. On balance, an estimated reduction in throughput time to one-ninth of that in a conventional factory appears reasonable.

## PRODUCT UNIFORMITY AND RELIABILITY

If the human-variability factor is eliminated, machines will produce products with rather small variability. This is tantamount to greater uniformity, which, if associated with a reliable product design, yields a reliable product.

## PRODUCT INNOVATION

In DOD production, as well as in production for the civilian sector, product innovation is motivated by field experience, the desire for cost reduction, and the desire to offer additional performance. Because of its inherent flexibility, programmable automation is expected to reduce the cost of tooling up for producing a new product (or a variation on an existing product), in much the same way that costs were reduced when N/C tools replaced manually controlled tools [36–41]. The Panel on Invention and Innovation of the Secretary of Commerce estimates that between 45 and 75 percent of the costs associated with a typical successful product innovation are attributable to tooling and manufacturing start-up expenses [42]. Moreover, there is a trend in American industry today toward customized products, even for so-called mass-produced items. Westinghouse's vice-president, Gordon Hurlbert, points out:

> We are switching from the production of large numbers of identical items to the production of large numbers of individually different yet similar items. Industry is becoming a large-scale job shop. [43]

The key characteristic of advanced automation in terms of product innovation is its flexibility—a characteristic which is lacking in conventional, hard automation.

## PRODUCTIVITY

It is difficult to define productivity in a universally meaningful way. However, an example drawn from American industrial experience with N/C machine tools

may be helpful. Productivity increases of from 150 to 400 percent are routinely reported by firms substituting N/C tools for conventional ones [44].[8] These increases usually reflect only the economics of metal cutting, not the contribution to overall factory economics of metal-cutting operations. Consequently, for firms engaged in the whole spectrum of manufacturing activities (fabrication, transfer, assembly, inspection, warehousing, etc.), large increases in metal-cutting productivity could produce a rather small increase in overall productivity for a complex assembly operation; for a parts-making operation, on the other hand, the increase could be substantial.

To realistically assess the potential of advanced automation in the manufacturing industry, it is essential that the concept be applied to as many internal factory operations as possible, so that the estimated impact will not be artificially diluted by arbitrary exclusion from activities and operations of significant cost. It is most important to recognize that this mix of activities varies greatly from one industry to another, so that the "payoff" may come in different areas for different industries. Nevertheless, in our opinion, it is unlikely that the payoff can be realized in most industries unless *all* parts of the factory are automated.

## SOCIAL IMPACTS

There has been a surge of labor dissatisfaction with jobs that are boring, repetitive, or dangerous. We will not speculate on the causes of the workers' attitudes but will merely point out that the programmable factory represents a means of abolishing this problem. Robots have already been used for some of these unpopular tasks (welding auto bodies, loading and unloading machines, moving hot forgings, etc.), but industry can go a great deal further.

The usual effects of automation will occur in this situation: A certain number of low-skill jobs will be eliminated, and some retraining of skilled personnel will be necessary. On the positive side, however, a certain number of more highly skilled jobs will be created by the need for programmers, repairmen, machine designers, etc. The introduction of N/C machine tools appears to have resulted in a net increase in the number of jobs, taking into account programmers, controls developers and builders, and field service personnel added and machinists, planners, and others subtracted.

One final social aspect, which has economic overtones, is the geographic mobility that automation could permit. Because the curve of unit cost versus volume produced for a programmable factory would be nearly flat, the economy of scale of centralized manufacturing facilities would no longer be applicable; and, if it appears desirable for social (or other) reasons, programmable factories, perhaps producing the same products, could be erected in several parts of the United States and abroad.

## INDUSTRY AND THE PROGRAMMABLE FACTORY

If progammable automation promises so many benefits, why hasn't industry developed and implemented these techniques? The answer to this question is somewhat complex. There are several forces interacting to produce today's state of manufacturing-technology economics and philosophy.

[8] Where *productivity* is defined as "shorter machining time per workpiece."

First, only a very few plants are planned from the beginning to utilize new concepts and approaches (e.g., Polaroid's new camera factory). The great bulk of U.S. industry uses approaches that improve slowly and much machinery that is outdated. No manufacturer can simply abandon his plant—even if it is outdated—and start over.[9] By contrast, German and Japanese plants, which were largely destroyed in World War II, were rebuilt with much higher productivity and more automated processes.

Second, relatively little thought and inventive effort have been expended on the programmable-factory concept. It is not certain that programmable automation will work, and the cost/benefit ratios cannot be determined until more—and preferably empirical—data become available.

Also, private industrial firms are very hesitant to invest the large development costs that probably would be required to make a fully automated factory feasible. In addition, competitors—both in the United States and elsewhere—could easily copy the techniques and thus leave the innovator with little return for his development dollars.

Finally, programmable automation is a new philosophical concept. It may take considerable time to convince people to change their concept of industrial automation processes.

[9] The replacement of an existing plant with a new plant is motivated by total cost considerations.

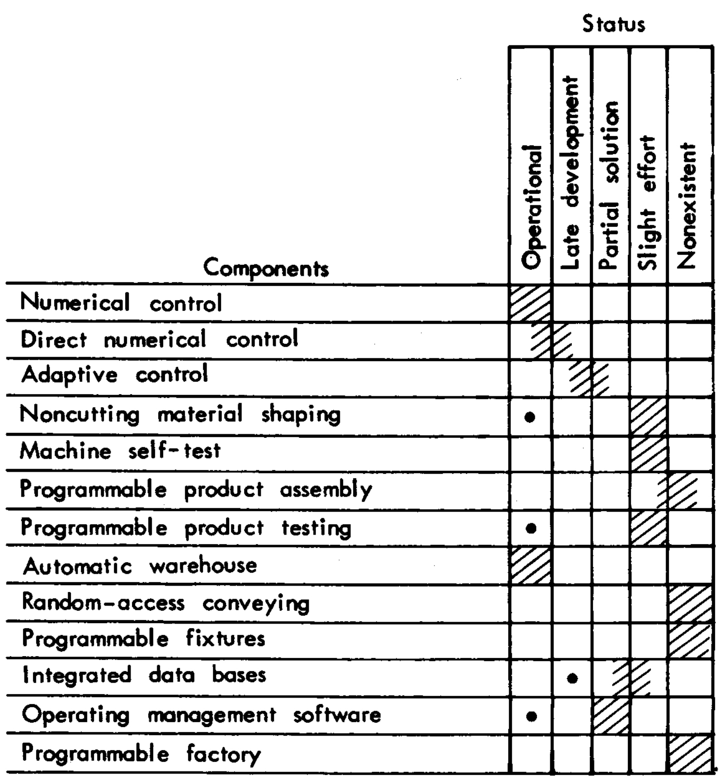
# IV. DEVELOPMENT REQUIREMENTS

## FACTORY COMPONENTS

The components needed for a flexible automated facility are currently in varying states of availability, ranging from commercially operational and readily available to nonexistent, with no developmental effort discernible. Figure 15 summarizes the current status of the principal required elements. Based on this status chart, we have identified a set of essential and desirable developments that would make the programmable factory feasible.

Those that we consider essential are:

1. Programmable assembly and test machines.
2. Data representation and control languages.
3. Factory scheduling and optimization.
4. Programmable conveyor systems and traffic control.
5. Integration of a complete prototype facility.
6. Design techniques for machine-assembled and tested products.




●Scattered example

Fig. 15—Status of required components for a programmable-automation facility

Developments that would be desirable are:

1. Programmable fixtures and pallets.
2. Hand-vision machines.
3. Uniform software interfaces between sensors and computers.

Each of these suggested developments is described briefly below. We expect that the duration of these development programs would range from two to four years. A demonstration of the fully automated concept—possibly through the construction of a prototype facility—would require six to eight years.

**Programmable Assembly and Test Machines**

The development of economically viable, programmable, flexible assembly machines is crucial to our concept of automated manufacturing. Consequently, we suggest that a major research and development effort should be undertaken to demonstrate the feasibility of such devices, preferably by several technological approaches. In forming the concept of a general-purpose assembly machine, the following questions must be investigated:

1. To what degree does part and subassembly orientation need to be maintained for parts presented to the assembly machine? (On the basis of our preliminary look, we believe that the conveyor and feed systems can maintain orientation sufficiently well, requiring no complex and costly approaches, such as scene analysis.)
2. What is the tradeoff between absolute precision and incremental precision based on closed-loop feedback and a limited search system? Among the many parameters to be considered are the costs of sensors and search mechanisms, the speed at which the processes can be performed with and without feedback, and the cost and complexity of a machine capable of maintaining high precision within a large working space.
3. What are the most effective techniques for providing final parts positioning for a multiplicity of parts, shapes, and sizes? One factor to be considered is the tradeoff between flexible and "hard" holding fixtures.
4. What are the most effective techniques for manipulating parts after they have been deposited in the assembly machine? Is there a fundamental set of primitive operations, such as rotation and translation, which is sufficient for all mechanical assembly operations? If so, what are these operations, and how many degrees of freedom are required to perform them?
5. What are the most effective techniques for bringing final joining tools (spot welders, magnetic shrink coils, cementing, etc.) into play?
6. What processes should be controlled entirely by local computation and feedback, rather than by closed information loops through the central computer? This question will involve an examination of the cost-effectiveness of tactile and/or visual feedback.

There are also major questions to be investigated concerning the programming and software requirements to control a general-purpose assembly machine. We shall discuss the software aspects below, under the heading "Data Representation and Control Languages."

Although considerable development work will be required to answer the questions listed above, we know of no fundamental problem that would prevent a development program from succeeding. One possible development program, aimed at

developing a programmable assembly machine that industry can afford, might include two principal techniques: (1) various versions of "blind" approaches which do not utilize vision but rely on tactile and other nonvision sensory feedback, and (2) approaches that use low-level vision techniques with cost-reduced scene analysis.

Development of the type of hand or gripper required by a general-purpose assembly machine in an industrial environment might be approached in two ways. One approach is to develop a very general-purpose "hand," having flexibility and degrees of freedom approximating those of the human hand, so that it can perform many varied grasping tasks under programmable control. A second approach is to provide a general-purpose "wrist," along with a bank of rather special-purpose grippers optimized for particular tasks, which could be inserted into or removed from the wrist automatically under programmed control. The study of hands and grippers is, of course, closely related to the studies of programmable assembly machines and should be coordinated or integrated with them. Because the control of a general-purpose hand is so complex, current concern with cost-effectiveness leads us to think that a wrist and grippers are preferable.

### Data Representation and Control Languages

The concept of programmable automation involves computer control of *all* aspects of the manufacturing process. As stated in Sec. II, information flow is required among the various components of the process: design, prototyping, production engineering, production. It is necessary to determine whether one data representation is sufficient for the information requirements of all components, or whether several specialized representations must be used, with some means of translation between them.

Intimately associated with the question of data representation is the choice of control language for programming the various processes within the manufacturing facility. Languages currently exist for programming N/C tools, but the type of language (and data representation) appropriate for programming an assembly machine with many degrees of freedom and dynamic feedback from tactile sensors has not been determined. The flexibility of the manufacturing facility is ultimately reflected in the flexibility inherent in the languages by which it is programmed. As new processes and techniques are introduced into the facility, the languages and data representations must be capable of assimilating these changes. The development of such languages and representations is within the state of the art of computer science, but this aspect of the development program must be given careful attention; the ease of programming and succinctness of data representation are major factors in the success of the concept of programmable automation.

The management of large, integrated data bases is now under intensive study [45,46]. Although the prognosis for these large data-management systems is good, a careful study must be made of the relationships among engineering-design files, engineering-change files, product-description files (bills of materials), and manufacturing-process files. These files are continually changing, and the effect of these changes on work in progress must be closely controlled.

### Factory Scheduling and Optimization

The programmable-automation factory is a logical extension of the present-day job-shop manufacturing facility. Job shops are characterized by the flow of a large number of different products (in batches) through a facility consisting of a collection of relatively flexible fabrication and assembly stations. Such facilities suffer from

the compounding of manufacturing problems, especially production planning and control, and inventory control (in particular, in-process inventory). The development program for an automated facility must solve these problems. Solutions will depend on the development of adequate computer-based planning tools and the successful management of large, integrated data bases. Clearly, data and planning are closely intertwined, so that the advance of one is affected by the advance of the other.

One important planning function is that of machine loading, i.e., deciding which machines should work on which parts at what times in order to optimize some measure of performance. Sequencing studies have been reported extensively in the operations research literature, but the complexity of the problem for realistic situations has defied deterministic solution. The trend is now toward simulations and heuristic methods with feasible and suboptimal solutions as the general outcome. This aspect of planning must be integrated with general requirements and capacity planning as well as inventory control. How much of the total planning-and-control problem can be solved by computerization is a serious question that must be addressed early in a development program.

### Conveyor System and Routing

A programmable, random-access conveyor system such as that described in Sec. II and shown in Fig. 4 would be a vital element in a programmable-automation facility. The particular configuration illustrated in Fig. 4—a ceiling-mounted grid—is only one of several possibilities; another would be self-propelled carts following cables buried in the factory floor. A study must be made of the various possibilities for a conveyor system with the desired properties, including an analysis of the interface between the conveyor system and the individual work stations. Is the concept of a robot acting as interface (as shown in Fig. 5) the best solution? How stringent is the requirement that the conveyor system maintain part orientation? What range of programmable pallets is required for material transfer?

The routing algorithm to be used for the automated conveyor system will also have to be developed. This aspect of the study must address such questions as, How many independent conveying devices must be under simultaneous control? How often should the routing be recalculated, and what is the magnitude of the calculations? The answers to many of these questions will depend on decisions about the topology of the conveyor network. It may be optimal to allow a crossover point between the x- and y-directions at each grid intersection. Fewer crossover points would probably reduce costs but would require greater traversal times and possibly a more complex routing algorithm. Research on the many tradeoffs and options concerning the conveyor mechanism is clearly required.

### Integration of a Prototype Facility

The various components of a programmable-automation facility—assembly machines, conveyor system, etc.—would lose much of their impact in isolation. The characteristics and interfaces of each component must be designed with the entire facility in mind. Therefore, it will be difficult to evaluate the effectiveness of any one part of the system alone.

The ultimate test of the viability of the concept of programmable automation would be the construction of a prototype manufacturing facility incorporating all of the components. While various development projects related to the components of an automated facility are under way, a study of the feasibility, costs, and benefits of constructing a prototype facility must be made. Such a prototype factory would

have several important advantages: industrial contractors could be drawn in at an early stage in its construction, resulting in a transfer to private industry of knowledge and capabilities regarding advanced automation; the facility could become a test of the viability of the concept; through operation of the prototype facility, costs and productivity could be studied with much more reliability than is possible through modeling alone.

The study of an integrated facility could be expedited by the parallel development of a computer model as the basis for a microeconomic analysis. Such an analysis would provide important data on which to base decisions of whether or not to construct a prototype facility. The potential benefits from programmable automation cited in Sec. III represent little more than educated speculation. To establish meaningful estimates of this potential, we must first develop a microeconomic description of an advanced facility. This, in turn, requires a much more definitive description of technical attributes such as production rate, required capital equipment, range of flexibility for a particular class of products, and time required for major product changeovers, and a somewhat lesser degree of speculation in assumed parameters. A method to develop these microestimates of technical and economic characteristics is discussed later, on pp. 35-36.

## Design Techniques for Machine-Assembled and Tested Products

We have found little research currently being performed on design techniques uniquely suited for machine-assembled and tested products. Studies of product design should be initiated that explicitly take into account the capabilities and limitations of flexible programmable assembly machines, rather than those of human assembly workers. Mechanical assembly machines should certainly not be required to assemble products in precisely the way they are assembled by human operators today; the unique characteristics of mechanical assembly devices should be considered as they affect methods of fastening, sequence of operations, and materials.

## Programmable Fixtures and Pallets

A common feature of conventional factories is the widespread use of fixtures to hold parts and subassemblies during forming, assembly, and inspection operations. These fixtures are often special-purpose designs that are used for just one or two steps in a manufacturing process consisting of dozens of steps.

The flexible factory we envision would be capable of producing (or potentially producing) many different products simultaneously, using common facilities; thus, an inordinately large inventory of such special-purpose fixtures would be required. An important part of a programmable-automation development program, therefore, is the exploration of alternative work-holding devices—programmable fixtures. These devices could be rapidly reconfigured within some fixed range (perhaps by an assembly machine) under programmable control. This degree of flexibility would allow rapid reconfiguration of this traditionally inflexible component of the manufacturing process—a capability that would be especially important to the DOD in reacting to mobilization or contingency requirements.

The investigation of programmable work-holding devices should address the following questions:

1. To what extent are such fixtures required in programmable automation? (They may be supplanted to some extent by additional hands or grippers on assembly/inspection machines.)

2. What is the relationship between programmable fixtures and the orientation-maintaining pallets used by the conveying system? (Pallets need some of the properties of programmable fixtures; perhaps the same device would suffice for both purposes.)
3. By what means can programmable flexibility be built into a fixture while retaining traditional requirements such as rigidity?

### Hand-Vision Machines

We do not think that it will be necessary to locate complex vision-sensing throughout the proposed automated facility. Sophistication in visual processing can probably be concentrated in a single work station specializing in the orientation of parts received from an outside source and in certain subtle inspection operations. It is necessary at this point to define the capabilities required of such a vision machine and to specify the hardware and software required to meet those capabilities. Current scene-analysis and pattern-recognition programs should be assessed and their applicability in an industrial environment evaluated. Within an automated facility, scene analysis can probably be aided by access to a data base containing information and specifications on objects to be recognized. Also, the environment can be controlled to some extent, for example, by machining or painting registration marks, using packaging materials having high contrast with packaged parts, etc.

### Uniform Software Interfaces

A programmable, automated manufacturing facility will rely to a very large extent on the use of sensors for feedback and inspection functions. A great variety of sensors are already commercially available, so the principal problem is probably one of engineering design for specific applications. On the other hand, it may be desirable to undertake a certain amount of investigation of the extent to which a uniform software interface can be developed for the interpretation of sensor signals. A uniform approach to the pattern-interpretation problem, parameterized suitably to take into account unique characteristics of various sensors, is certainly preferable to writing a unique interpretation algorithm for every distinct sensor type used within the manufacturing facility. The development program should estimate the extent to which a uniform approach to the sensor-interpretation problem is in fact possible.

## SIMULATION OF A CONVENTIONAL FACTORY

As mentioned earlier in this section, a mathematical model of a programmable-automation facility would be a valuable tool for performing a microeconomic analysis. The method of analysis we suggest is as follows. We would select and describe an existing product and manufacturing facility to be tested against a highly automated facility. The existing facility—our conventional factory—and the automated facility would be designed to produce the same product at the same rate. By estimating and aggregating the costs of individual components (machine tools, floor space, conveyor systems, etc.) of the conventional design, it will be possible to develop overall capital costs for the automated facility; operating and maintenance costs must be developed from estimates of required labor and labor rates. The advantages and disadvantages of this method of analysis are given in Table 4.

Table 4

ADVANTAGES AND DISADVANTAGES OF SIMULATION METHOD OF COMPARATIVE ANALYSIS

| Advantages | Disadvantages |
|---|---|
| (1) Focus is on real-world product and process. | (1) Strong dependence upon industry cooperation is necessary; both technical (easy) and cost (difficult) data must be obtained from industry. |
| (2) No design of conventional facility required. | (2) Conventional facility assumed may be obsolete or designed to make more than one product; equitable cost comparisons are difficult to develop. |
| (3) Experienced industry members may be valuable sources of information on product history and specific production problems. | (3) Since everything from product design to assembly methods may be quite different for the programmable factory, a one-for-one comparison of steps will not be feasible. |
| (4) Existence of an operational process in current production minimizes possibility of overlooking factory functions. | (4) Available time and budget may be insufficient to design complete automated facility; inappropriate costs of conventional facility are difficult to separate out. |

Disadvantage (3) may require costing the conventional process in sum total, rather than as the aggregation of a number of elements that have no parallel in the programmable factory.

In summary, an assessment of the impact of programmable automation on each *element* of the manufacturing process is not likely to yield valid results, but valid economic estimates of the *overall manufacturing process* appear to be possible.

## EVALUATION OF IMPACT ON BUSINESS STRUCTURE

The potential impact of advanced automation on the way a firm might do business is another complex issue to consider. For example, one characteristic of conventional manufacturing facilities is their inertia—workers cannot be hired, trained, or fired at will to respond to moderate changes in demand. Consequently, conventional facilities rely on large standing inventories as production-smoothing devices. Equally important, the inertia of conventional facilities makes it difficult for manufacturers to respond rapidly to specific requests for products not in stock. Problems attributable to inventories and rapid response are being cited with increasing frequency by American industry [44,47,48].

An automated facility, on the other hand, could expand its operation from one to two or three shifts a day with relative ease, as is done in computational facilities today. This feature could be used as a production-smoothing alternative to large inventories and/or as a rapid-response mechanism to satisfy special or critical requests. Even if it were necessary to maintain the employment level during periods

of little or no demand, the labor costs associated with an advanced facility are much smaller than those of a conventional one, and economic benefits could still be derived from reducing inventories or using quick-response services that other firms could not offer. This is but one limited example of how the operations of an automated firm might differ from a conventional one. However, by stressing four fundamental attributes of an automated firm—flexibility, speed, economic operation over a wide range of production lot sizes, and increased independence from labor problems—it is a simple matter to devise a multitude of business scenarios in which conventional facilities could not compete—or operate at all. These scenarios, though, represent only one side of the coin and thus may be misleading.

It may be that to derive full benefit from the attributes of automation cited above it will be necessary for firms to change their management, design, marketing, and merchandising strategies radically. Without such changes, or a willingness to generally accept them, the benefits of advanced automation would be much diluted. Equally important, it may be impossible to design an automated factory that operates with little human intervention in precisely the way a conventional factory operates.

The intent of research in this area should be to make clear in a qualitative manner the kinds of changes advanced automation might imply for the manufacturing industry. Whenever possible, quantitative estimates of the significance of these changes should be developed. Future investigations should also focus on implications that bear directly on contemporary business problems (e.g., international trade) and/or on major contributors to manufacturing cost.

## EXAMINATION OF SOCIAL ISSUES

Because a factory is an institution shaped and guided almost exclusively by economic considerations, it could be argued that all the potential implications of a highly automated factory could be gauged by one or more economic measures. While this is probably generally true, economic criteria cannot measure easily, if at all, certain qualitative attributes of advanced automation. And these "softer" attributes may ultimately prove as significant to American society as the economic and technical attributes that are more amenable to quantitative evaluation. Consequently, a research program should address certain social concerns associated with advanced automation.

It would again be premature to suggest in exactly what areas the social impact of this concept will be greatest, but certain broad areas of potential significance can be outlined.

Probably the most recurrent concern of social analysts dealing with automation has been that of employment. Some specific issues are summarized in Table 5, together with attributes of advanced automation that might have a bearing on them.

In addition to the pure employment issues, advanced automation may also bear on certain employment-related issues, some of which are summarized in Table 6.

Finally, advanced automation has evident potential for changing the quality of life significantly in terms of the nature and quality of the goods and services consumed by a society. Examples are given in Table 7.

The issues cited above by no means constitute an exhaustive statement of the potential social implications of advanced automation. The selection of issues for examination must await increased familiarity with the attributes of programmable automation.

Table 5

POTENTIAL IMPACTS OF PROGRAMMABLE AUTOMATION ON EMPLOYMENT ISSUES

| Issue | Attributes of Automated Factory |
|---|---|
| (1) Worker displacement by equipment. | (1) Near independence from certain internal labor activities but a growing dependence on maintenance activities; also a strong dependence on labor force of suppliers and product distributors. |
| (2) Worker displacement through loss of jobs to foreign competition. | (2) Same as (1) with strong emphasis on productivity of manufacturing process. |
| (3) Demography/mobility of workers; urban concentration and importance of transportation costs of finished goods. | (3) Speed and flexibility of production; lower capital costs, permitting alternative inventory, merchandising, and transportation concepts; new jobs created by the introduction of new machines. |

Table 6

POTENTIAL IMPACTS OF PROGRAMMABLE AUTOMATION ON EMPLOYMENT-RELATED ISSUES

| Issue | Attributes of Automated Factory |
|---|---|
| (1) Undesirability of certain tasks, especially mindless tasks such as working on assembly lines. | (1) Upgrading of skills and job tasks. |
| (2) Increasing education and aspirations of workers. | (2) Same as (1) with emphasis on professional-technical/laborer ratios. |
| (3) Expansion of service industries. | (3) New business scenarios, which create or expand service industries. |
| (4) Skills required for successful management of a business firm. | (4) Management may be reconstituted and may operate in a radically different way. |

Table 7

POTENTIAL IMPACTS OF PROGRAMMABLE AUTOMATION ON QUALITY-OF-LIFE ISSUES

| Issue | Attributes of Automated Factory |
|---|---|
| (1) Cost of goods and services; standard of living. | (1) Increased productivity resulting in lower manufacturing costs. |
| (2) Quality and integrity of products. | (2) Elimination of human error in manufacturing; higher standards (precision, etc.) than are practical for workers. |
| (3) Increasing customization and personalization of goods and services. | (3) Flexibility and economic operation over a wide spectrum of economic lot sizes. |
| (4) A growing and easily accessed base of proven engineering practice. | (4) Retention of good features of previous models through use of memory devices. |
| (5) Boring and hazardous jobs. | (5) Elimination of this issue. |

## PRODUCT CLASSES

To assess the potential impact of programmable automation on DOD procurement, we must understand which product classes benefit most from this type of automated manufacture. It will then be possible to estimate the percentage of the DOD's procurement expenditure that would be affected by automated manufacture of those classes. We have assumed that small electromechanical devices constitute a product class upon which programmable automation would have a large impact. However, that assumption should be examined in more detail. The study of product classes should include the nature of the design, the size of production lots, the number of engineering-change orders, the size and complexity of the product, the labor content, and other factors in current production techniques.

## MANAGEMENT AND COORDINATION OF A DEVELOPMENT PROGRAM

One of the most difficult tasks in a development program in programmable automation is that of management and coordination. Most of the characteristics of automated systems discussed above are highly interrelated: How an assembly machine is programmed depends to a large extent on its degrees of freedom and similar mechanical attributes; those attributes in turn depend on its reliance on sensory feedback, its interface with the conveyor mechanism, its reliance on fixtures, etc.

Clearly, a microeconomic model of the programmable-automation facility can also be a prime tool in managing and coordinating the various components of the development program. As characteristics of machines or processes become known in more detail, they should be included in the model so that their consistency with other aspects of the facility can be checked. As the development program proceeds, the description of the various components and the interrelationships among them will become more evident from the governing model. Consequently, the economic analysis based on the model will become more precise. We feel that the model to be developed must have sufficient depth and precision to form the basis for a national program stimulating the development of programmable automation.

# V. CONCLUDING REMARKS

As we have mentioned above, the study reported here is a preliminary examination, and the analysis is far from complete. Our tentative findings are summarized below:

1. Programmable automation appears to be technologically feasible, although its implementation will require innovations and a focused development program over a period of at least five years.
2. The development of programmable automation by industry is proceeding very slowly and in piecemeal fashion, for several reasons:
   a. The risk of being copied by rival companies is too great to justify an expensive, lengthy development effort by any single industry member.
   b. Several elements of the programmable factory are not available in the marketplace.
   c. The entire manufacturing process needs to be considered; such a study would require large resources and an interdisciplinary effort.
   d. Not enough data are available on potential benefits and development costs.
3. Because of the factors listed under Item 2 above, we believe that the developmental effort would have to be underwritten by the Federal government to a significant extent, as happened in the case of N/C machine tools [49] and integrated-circuit technology [50].
4. The impact of programmable automation could be profound. Major areas of potential impact are:
   a. *Increased productivity.* Doubling or tripling of productivity in some industries could be expected, resulting in part from reduced capital and operating costs.
   b. *Increased product quality and safety,* due to more uniform production and inspection, more thorough inspection, and more complete information about manufacture for error tracing and product recall.
   c. *The potential for decentralization of production.* Economies that presently result from forming pools of special-purpose conventional machinery and special skills will have less significance.
   d. *Changes in the characteristics of the management structure and work force.* The potential effects of these changes are poorly understood at this time.
   e. *Product innovation.* The potential for customized products could create entirely new demands and significantly affect consumer-oriented industries.
5. Cost-effectiveness of programmable automation is largely an unknown. A completely automated factory could prove highly cost-effective, whereas a random-access conveyor in today's factory, as a stand-alone item of flexible automation, may not be cost-effective at all. So far, our preliminary evaluation has shown the most favorable results for a complete flexibly programmed, automated factory. Of course, any decision to actually construct such a factory must be carefully considered in the light of a thorough cost-benefit analysis.
6. We reemphasize that the economic estimates we have made are very rough. The full impact of programmable automation cannot be properly assessed without an in-depth study of the economics of discrete-product manufacturing and procurement, including possible alternatives to the automation concept. Of course,

the research and development costs associated with each option must be carefully weighed against the estimated benefits.

Although it will be necessary to automate an entire manufacturing facility to realize the maximum impact of programmable automation, this does not negate the need for, or value of, research on individual components. Each of the study areas we have outlined has its own standing as a valid manufacturing problem and should be pursued as such.

# Appendix A

# SUMMARY OF INTERVIEWS AND ORGANIZATIONS VISITED

I. Governmental Agencies

| Persons Contacted and Organization | Date | Participating Automation Study Members |
|---|---|---|
| 1. Col. L. A. Staszak<br>OSD (I&L) | September 7, 1971 | Brewer |
| 2. D. W. Wells<br>Air Force DCS (R&D)<br>Director of Dev. & Acquisition<br>Industrial Resource Division | September 14, 1971 | Anderson, Brewer |
| 3. Lt. Col. C. W. Groover<br>OSD (Sys. Analysis)<br>Logistic Guidance | September 14, 1971 | Anderson, Brewer |
| 4. E. Saunders<br>Office of Emergency Preparedness<br>Deputy Director--Natural Resource Analysis | September 14, 1971 | Anderson, Brewer |
| 5. C. Nelson<br>Materials Lab<br>Air Force Logistics Center<br>Wright-Patterson A.F.B. | September 23, 1971 | Roseen, Sibley |
| 6. M. Waller<br>U.S.A. Advanced Materiel Concepts Agency<br>Alexandria, Va. | October 8, 1971 | Anderson |
| 7. R. Davis<br>National Bureau of Standards<br>Gaithersburg, Md. | February 28, 1972 | Anderson, Brewer, Ellis, Uncapher |

II. Nonprofit Organizations and Universities

| | Persons Contacted and Organization | Date | Participating Automation Study Members |
|---|---|---|---|
| 1. | M. Minsky<br>Project MAC<br>M.I.T. | August 12, 1971 | Anderson, Davis, Ellis, Groner, Sibley |
| 2. | C. Rosen<br>S.R.I. | August 25, 1971 | Anderson, Groner |
| 3. | G. Bailey<br>American Ordnance Association<br>Mobilization Readiness Division | September 14, 1971 | Anderson, Brewer |
| 4. | W. House<br>National Academy of Sciences | September 15, 1971 | Anderson |
| 5. | W. Jamieson<br>Battelle Institute | September 22, 1971 | Sibley, Roseen |
| 6. | G. T. Wachter<br>S.R.I. | November 16, 1971 | Anderson, Sibley |
| 7. | J. McCarthy<br>Stanford University | December 22, 1971 | Anderson, Ellis, Sibley, Uncapher |
| 8. | J. Nevins<br>Draper Laboratory<br>M.I.T. | March 8, 1972 | Groner |
| 9. | D. M. Towne<br>U.S.C. Behavioral Technology Lab | May 19, 1972 | Anderson, Sibley |

III. Industries

| | | | |
|---|---|---|---|
| 1. | D. Bickle<br>Lockheed Aircraft<br>Burbank, Calif. | August 4, 1971 | Anderson, Davis, Ellis, Groner, Sibley |
| 2. | S. Groner<br>A.M.F.<br>New York, N.Y. | August 9, 1971 | Anderson, Davis, Ellis, Groner, Sibley |
| 3. | T. H. Lindbom<br>Unimation, Inc.<br>Danbury, Conn. | August 10, 1971 | Anderson, Davis, Ellis, Groner, Sibley |
| 4. | J. Serieno<br>A.M.F.<br>York, Pa. | August 11, 1971 | Anderson, Davis, Ellis, Groner, Sibley |

III. Industries--Continued

| Persons Contacted and Organization | Date | Participating Automation Study Members |
|---|---|---|
| 5. M. Goulder<br>Saunders Associates<br>Nashua, N.H. | August 13, 1971 | Anderson, Davis, Ellis, Groner, Sibley |
| 6. H. Mayes<br>Fairchild Semiconductor<br>Palo Alto, Calif. | August 20, 1971 | Groner |
| 7. W. Rogers<br>A.M.F.<br>Voit Division<br>Santa Ana, Calif. | August 27, 1971 | Groner, Sibley |
| 8. B. Rome<br>A.M.F.<br>Tire Equipment Division<br>Santa Ana, Calif. | August 27, 1971 | Groner, Sibley |
| 9. G. Dodd<br>G.M. Tech. Center<br>Warren, Mich. | September 24, 1971 | Sibley |
| 10. R. Lewis<br>G.M. Tech. Center<br>Warren, Mich. | September 24, 1971 | Sibley |
| 11. K. Ruff<br>G.M. Tech. Center<br>Warren, Mich. | September 24, 1971 | Sibley |
| 12. H. Martin<br>I.B.M.<br>Advanced Systems Development Division<br>Mohansic, N.Y. | October 5, 1971 | Anderson, Ellis, Uncapher |
| 13. J. Wilford<br>I.B.M.<br>Components Division<br>East Fishkill, N.Y. | October 6, 1971 | Anderson, Ellis, Uncapher |
| 14. J. Massara<br>I.B.M.<br>Federal Systems Division<br>Oswego, N.Y. | October 7, 1971 | Anderson |

III. Industries--Continued

| | Persons Contacted and Organization | Date | Participating Automation Study Members |
|---|---|---|---|
| 15. | W. Winters<br>G. M. Tech. Center<br>Warren, Mich. | October 11, 1971 | Brewer, Groner, Sibley |
| 16. | R. Glorio<br>Versatran<br>Detroit, Mich. | October 12, 1971 | Brewer, Groner, Sibley |
| 17. | J. O'Reilly<br>Ford Motor Company<br>World Headquarters<br>Detroit, Mich. | October 12, 1971 | Brewer, Groner, Sibley |
| 18. | W. Spurgeon<br>Bendix Research Labs<br>Southfield, Mich. | October 13, 1971 | Brewer, Groner, Sibley |
| 19. | K. Boyd<br>Kearney and Trecker<br>Milwaukee, Wisc. | October 14, 1971 | Brewer, Groner, Sibley |
| 20. | F. Long<br>W. F. and John Barnes Company<br>Rockford, Ill. | October 15, 1971 | Brewer, Groner, Sibley |
| 21. | P. Wood<br>Sundstrand<br>Belvedere, Ill. | October 16, 1971 | Brewer, Groner, Sibley |
| 22. | H. Davis<br>Hughes Aircraft Company<br>Tucson, Ariz. | October 15, 1971 | Anderson, Ellis |
| 23. | J. Linden<br>Hughes Aircraft Company<br>El Segundo, Calif. | November 5, 1971 | Davis, Groner, Sibley |
| 24. | H. Laitin<br>Hughes Aircraft Company<br>Culver City, Calif. | December 14, 1971 | Anderson, Brewer, Davis, Ellis, Roseen, Sibley, Uncapher |
| 25. | T. Fischer<br>I.B.M.<br>San Jose, Calif. | January 13, 1972 | Groner, Sibley |
| 26. | R. W. Boesel<br>Lockheed MSD<br>Sunnyvale, Calif. | January 14, 1972 | Groner, Sibley |

III. Industries--Continued

| Persons Contacted and Organization | Date | Participating Automation Study Members |
|---|---|---|
| 27. H. Davis<br>Hughes Aircraft Company<br>Tucson, Ariz. | January 21, 1972 | Anderson, Brewer, Ellis, Groner, Sibley, Roseen |
| 28. R. Nelson<br>Mattel Toy Company<br>Hawthorne, Calif. | February 25, 1972 | Sibley |
| 29. L. W. Salisbury<br>Litton-Melonics Division<br>Canoga Park, Calif. | March 1, 1972 | Sibley |
| 30. T. Bernard<br>Rohr Aircraft Company<br>Chula Vista, Calif. | March 10, 1972 | Brewer, Sibley |
| 31. G. Gunning<br>Price Pfister<br>Pacoima, Calif. | March 30, 1972 | Sibley |
| 32. D. Nelson<br>Baker Oil Tool Inc.<br>Los Angeles, Calif. | April 11, 1972 | Brewer, Sibley |
| 33. C. A. Kopeny<br>California Computer Products<br>Anaheim, Calif. | May 12, 1972 | Anderson, Brewer, Sibley, Roseen |

IV. Conferences

| | | |
|---|---|---|
| 1. Society of Manufacturing Engineers<br>CAD/CAM Conference<br>Atlanta, Ga. | February 1-3, 1972 | Sibley |
| 2. Engineering Foundation Conference on Pattern Information Processing<br>Airlie House, Va. | February 23-27, 1972 | Anderson |
| 3. IITRI, Chicago<br>Second International Symposium on Industrial Robots | May 16-18, 1972 | Brewer |

# Appendix B

## SOME MODERN MEASURING AND TESTING TECHNIQUES

1. Length and position

   a. Air gauge—requires special-purpose gauge block [51, p. 419]
   b. Optical comparator—object is magnified and compared with mask [51, p. 421]
   c. N/C probe—measures distance between specified and actual positions; accuracy = 0.0001 in. [52]
   d. Analog resolver—rotor voltage = 0 when motor-driven to desired position; accuracy = 0.01 mm [53]
   e. Digital/optical—crossings of alternate opaque, transparent elements are counted; resolution = 1m [53]
   f. Laser interferometer—limited to range of 60-100 in. unless corrected for air turbulence, pressure, temperature, and humidity [54]; accuracy = 0.00005 in. in commercial unit [55]
   g. Rangefinder—receptor (e.g., TV camera) locates reflected spot or slit; geometry determines object location [56]
   h. Fiduciary marks—object is visually located with respect to locating marks; position is computed using transformation matrix

2. Pressure

   a. Wire strain gauge
   b. Piezoresistive semiconductor device—greater sensitivity and mechanical reliability; smaller, simpler, higher output levels as compared with wire device; requires temperature compensation; in industrial applications: range = 0–20,000 psi, sensitivity = 2–10 mv/psi [57]; use as on-off switches in Japanese robot hand [58]

3. Torque [59]

   a. Strain gauge—fast response; slip rings required
   b. Magnetic device—limited response; electronically complex
   c. Electrical phase displacement—direct electrical output but complex circuitry
   d. Optical device—simple circuitry; no slip rings; requires view of disk

4. Vibration

   a. Accelerometer

5. Surface finish

   a. Stylus moving over surface—works somewhat like phonograph [51, pp. 429-433]
   b. Laser + pattern recognition—laser lights surface; reflected pattern is analyzed [60]

6. Flatness [51, pp. 425-427]

   a. Monochromatic light + optical flat—laser may be used; rings in interference pattern counted

7. Alignment [51, pp. 427-429]

   a. Optical tooling—usually telescope + reflector; laser is a good light source

8. Tensile test [51, pp. 30-38]

   a. Bar of material is placed under stress, and strain is measured—used for determining stiffness, tensile strength, ductility, and brittleness

9. Hardness

   a. Brinell or Rockwell tester—penetrator is pushed into material, and resulting impression size is measured [51, pp. 38-41]
   b. Magnetic technique—samples of test material and of same material with known hardness are placed in magnetic coils; flux density difference is a good measure of hardness difference; rapid and does not require surface machining [61]

10. Temperature

    a. Thermocouple
    b. Thermocouple formed by tool tip in contact with material being shaped—used in Bendix adaptive control [62]
    c. Thermistor (thermoresistive semiconductor device)—small, fast, high temperature coefficient, high resistance [63]

11. Bond quality [64,65]

    a. IR (Infrared)—apply temperature differential and look (with point detector or IR camera) for heat-flow irregularities; output requires interpretation; noncontact, total coverage of object fast (except for point-by-point scanning and interpretation)

12. Internal flaws

    a. IR—see item 11.a.
    b. X-ray and Gamma-ray—radiation passes through material depending on its thickness, thus voids show up; requires interpretation [51, p. 47]
    c. Ultrasonics—wave transmitter is coupled to part by oil or water; discontinuity causes reflection; location, size, and depth of flaw can be determined by interpreting received signal; used for welding inspection rates to 50 ft/hr [66]

13. Surface flaws

    a. IR—see item 11.a.
    b. Laser—see item 5.b.
    c. Ultrasonics—see item 12.c.
    d. Dye penetrant—dye is drawn into surface discontinuities by capillary action; excess is washed off; remaining dye stains developer, which also blots slightly; part is examined manually or with pattern recognition; timing of certain operations is critical; therefore, automatic system is desirable [66]
    e. Magnetic method—magnetic particles adhere to and outline cracks in magnetic ferrous materials; otherwise works like dye penetrant [51, p. 48]

14. Optical sensors

a. Light sources

- General lighting over scene
- Slide projector—e.g., for grid coding or slit rangefinding [56,67]
- Fiber-optic pipes [68]
- Laser

b. Point or array receptors—for on-off or gray-scale indication

- Photocell
- Fiber optics [68]
- Light-sensitive semiconductors—400:1; light intensity range with phototransistors [69]

c. Scanner receptors—require interpretation

- Flying-spot scanner
- Vidicon—fast; problems: very high data rates, low resolution, noise, jitter, quantization error [70]
- Image dissector—like Vidicon but better resolution, less noise, slower [70]

15. Electronic circuit testing [71]

Advanced systems use adaptors (to provide a common measuring system/circuit interface) and are computer-controlled (for flexible test-sequence generation). Several test-set programming languages are available. Adaptive approaches and "autoprogramming translators" use a good circuit to ease the programming job. Localization of error depends on number of probes and tests for both analog and digital circuits. Costs are $30,000–$300,000, depending on the number of test stations, the degree of flexibility, and the amount of output processing.

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